NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1353

A Method for Calculating Steady-State Thrust and Flow-Rate Levels for Mariner IV Type Attitude Control Nitrogen Gas Jets

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Preface

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

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Abstract

The work presented in this report is limited to steady-state thrust and flow-rate determinations versus varying design parameters for the *Mariner IV* type ball valve-nozzle configurations, where a subsonic orifice is in series with a sonic nozzle throat separated by a chamber volume of approximately 0.2 cc. Design variables investigated included inlet pressure of 10 to 35 psi, ambient pressure of 1×10^{-6} torr, inlet temperature of -100 to $+150$°C, valve orifice area of 5×10^{-4} to 40×10^{-4} in.^{2}, nozzle throat diameter of 5×10^{-3} to 50×10^{-3} in., nozzle geometric area ratio of 25 to 275, and nozzle cone half-angle of 15 to 40 deg.

Thrust levels considered are in the millipound range using cold nitrogen gas as the propellant. The equations used to determine nozzle losses are based on flat-plate analogies. The mathematical formulation and IBM 1620 computer program used in this analysis are also described.

A Method for Calculating Steady-State Thrust and Flow-Rate Levels for *Mariner IV* Type Attitude Control Nitrogen Gas Jets

I. Introduction

JPL's *Ranger* and *Mariner* spacecraft represent major successes in unmanned lunar and planetary exploration of space. For attitude control of these spacecraft, redundant cold nitrogen gas systems were used. Based on previous successes, it is anticipated that similar nitrogen gas systems will be employed on planetary spacecraft missions in the late 1960s and early 1970s. As mission durations and trajectory restrictions increase and as spacecraft inertias and angular rate requirements vary, a more accurate method of determining thrust, impulse, and flow-rate levels delivered by attitude control gas jets prior to launch becomes very desirable. It is also very useful in design and development of attitude control gas systems to understand thoroughly how these levels are affected by various design parameters.

This report represents an initial investigation into this area. The basic objective is to establish a set of parametric curves that can be used to obtain first approximation, or better, design data necessary to fabricate attitude control gas jets to meet specific mission requirements. The restraints on this initial investigation include the following:

(1) Space vacuum conditions apply.

(2) Steady-state case only will be attempted.

(3) Estimates will be made of losses associated with nozzle flow.

(4) Design parameters in ranges centered about the *Mariner IV* gas system will be investigated.

(5) Only nitrogen will be considered as the working gas.

Although not discussed herein, test apparatus and various valve-nozzle configurations will be fabricated and tests will be run to verify the results of this analysis. The testing effort is running concurrently with the analysis.

An IBM 1620 computer was utilized in this analysis because of its availability at the time this effort was being initiated.

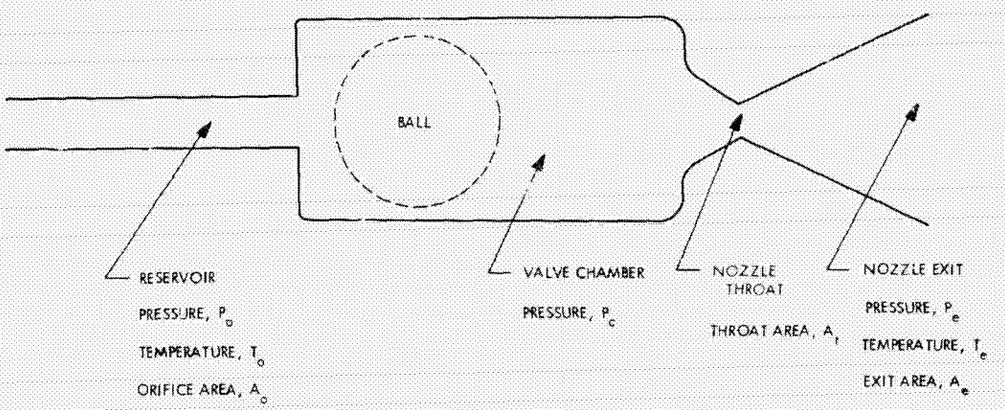


Fig. 1. Analytical model of *Mariner IV* valve

With the completion of this initial investigation, an analysis of the pulsed mode of operation (transient case) will be undertaken.

II. Analytical Derivation

The model used for the derivation of the equations below is shown in Fig. 1. This model is similar, but not limited to *Mariner IV* flight hardware (Figs. 2, 3, and 4). The model consists of a series combination of upstream piping and two downstream restrictions, an orifice (not necessarily a ball valve), and a nozzle. Although not covered in this report, with appropriate modifications in the derivation, this model can easily be made to include many types of thruster designs, including those in which the gas is heated before being expelled through the nozzle and those containing more than two downstream restrictions. For the steady-state analysis, the flow is assumed to be subsonic in the valve and sonic at the throat.

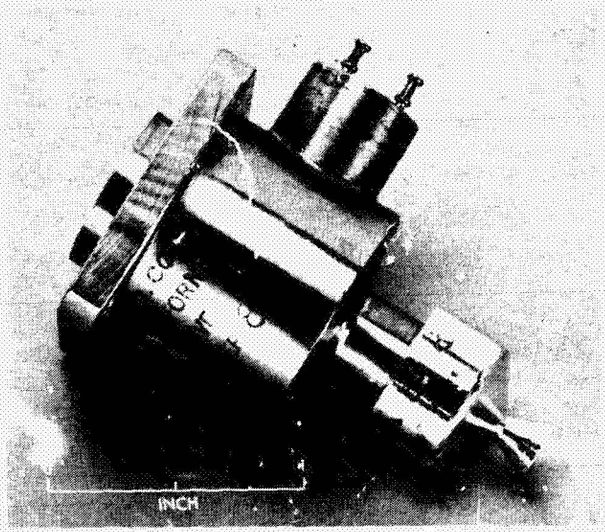


Fig. 2. *Mariner IV* reaction jet valve and nozzle

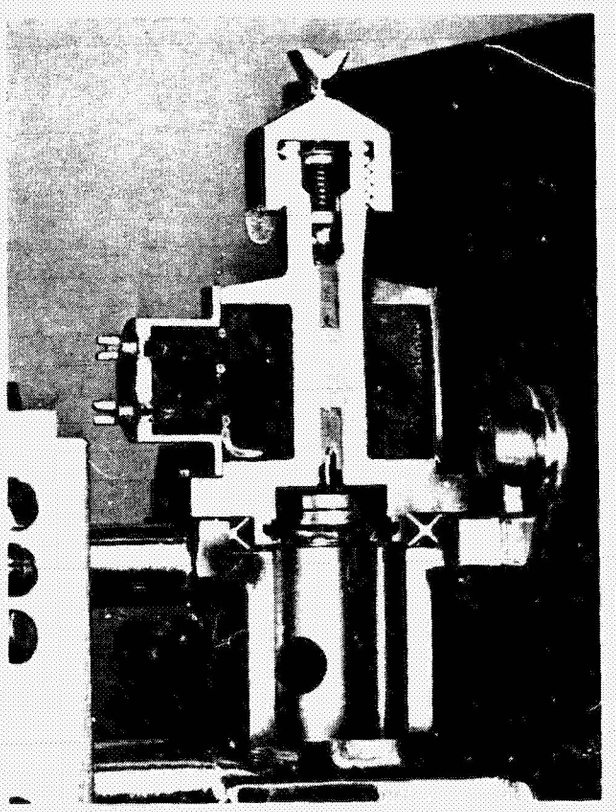


Fig. 3. Cutaway of *Mariner IV* thruster

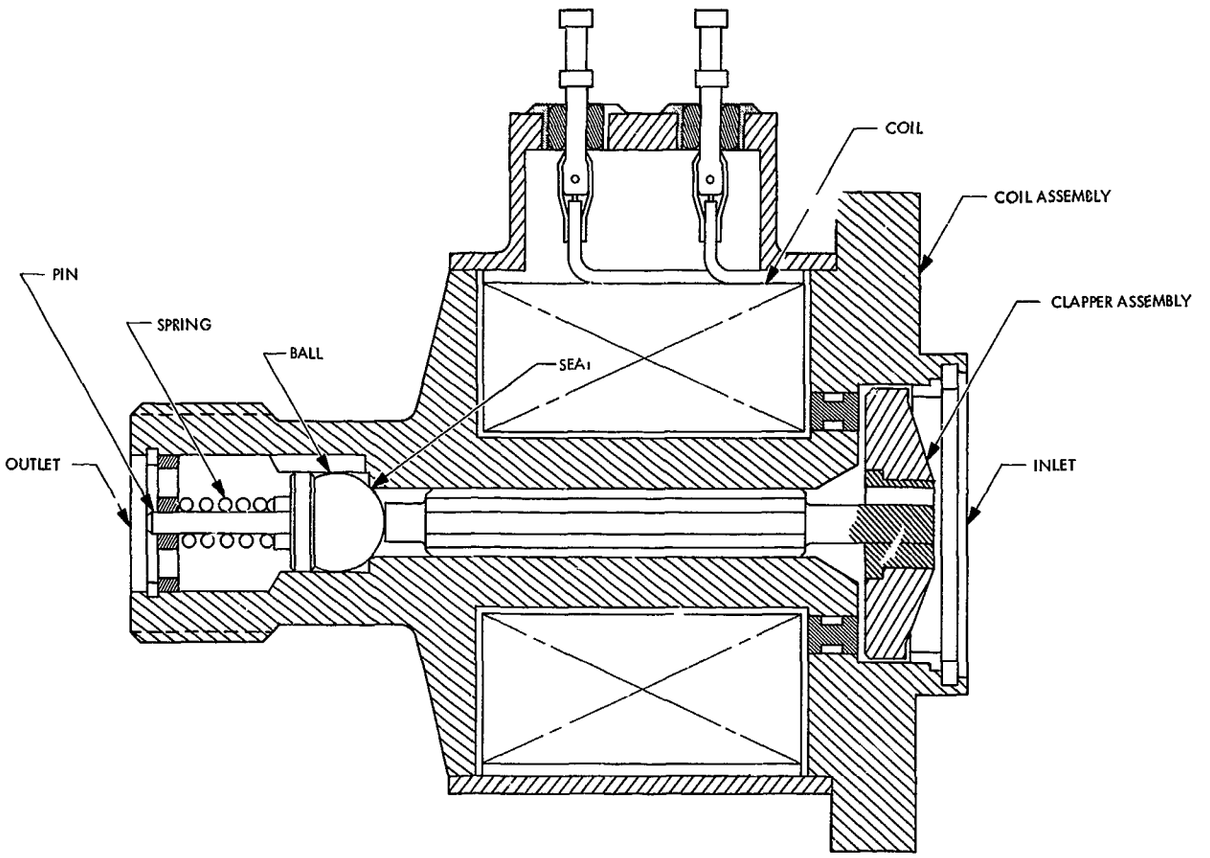


Fig. 4. Section view of *Mariner IV* valve

The flow through the valve-nozzle combination is treated as one-dimensional, isentropic, and compressible. Cold nitrogen gas, the propellant used in the analysis, is considered ideal. It is assumed that no thrust loss is caused by vapor condensation in the nozzle, a condition which may exist with other propellants. The gas is assumed to be at stagnation conditions upstream of the valve seat. The majority of the pressure drop between the valve manifold and chamber (volume between valve seat and nozzle) is assumed to occur at the valve seat. For the *Mariner IV* with a ball valve, the flow path across the valve is an annular orifice. The relationship between the annular orifice area and the ball travel is derived in Appendix A.

The assumptions for the simplified treatment of the nozzle boundary layer, based on flat plate theory and its effect on thrust loss, is outlined in previous work[1].

Variation in thrust level caused by thermal expansion of the nozzle throat is considered negligible.

Euler's equation, applied to the valve orifice, is

$$\frac{dP}{\rho} + \frac{VdV}{g_o} = 0 \tag{1}$$

For an isentropic process

$$\frac{P}{\rho^\gamma} = \text{Constant} = C \tag{2}$$

Substituting Eq. (2) into Eq. (1), and integrating, gives:

$$C^{1/\gamma}\int_o^c \frac{dP}{P^{1/\gamma}} + \frac{1}{g_o}\int_o^c VdV = 0 \tag{3}$$

or

$$C^{1/\gamma}\left(\frac{\gamma}{\gamma-1}\right)\left[P_c^{\frac{\gamma-1}{\gamma}} - P_o^{\frac{\gamma-1}{\gamma}}\right] + \frac{V_c^2 - V_o^2}{2g_o} = 0 \tag{4}$$

From Eq. (2)

$$\frac{P_o^{1/\gamma}}{\rho_o} = C^{1/\gamma} = \frac{P_c^{1/\gamma}}{\rho_c} \tag{5}$$

[1]Dayman, B., Jr., "Simplified Theoretical Estimates of Thrust Losses in Miniature Nozzles," Internal Memorandum, Jet Propulsion Laboratory, Pasadena, Calif.

Equation (4) then becomes for $V_o = 0$ (stagnation)

$$\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{P_o}{\rho_o}\right)\left(\frac{P_c}{P_o}\right)^{\frac{\gamma-1}{\gamma}} + \frac{V^2}{2g_o} = \left(\frac{\gamma}{\gamma-1}\right)\left(\frac{P_o}{\rho_o}\right) \tag{6}$$

The flow rate through the valve is given by

$$\omega_v = \rho C_{dv} A_0 V \tag{7}$$

where

A_o = effective valve area

When Eq. (6) is solved for V and is substituted into Eq. (7)

$$\omega_v = C_{dv}A_0\rho_0\left(\frac{P_c}{P_o}\right)^{1/\gamma} \times \left\{2g_o\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{P_o}{\rho_o}\right)\left[1-\left(\frac{P_c}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2} \tag{8}$$

From the equation of state

$$\rho_o = \frac{P_o}{RT_r} \tag{9}$$

Therefore, the flow rate, ω_v, is

$$\omega_v = C_{dv}A_0P_o\left(\frac{P_c}{P_o}\right)^{1/\gamma}\left\{\left(\frac{2g_o}{RT_r}\right)\left(\frac{\gamma}{\gamma-1}\right)\left[1-\left(\frac{P_c}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2} \tag{10}$$

The specific impulse, I_{sp}, is defined as

$$I_{sp} = \frac{F}{\omega_t} \text{ or } \omega_t = \frac{F}{I_{sp}} \tag{11}$$

F = maximum theoretical nozzle thrust, lb

ω_t = nozzle flow rate, lb/s

Since the nozzle is exhausting into vacuum, the maximum theoretical thrust is given by

$$F = P_cA_t\left[\frac{2\gamma^2}{(\gamma-1)}\left(\frac{2}{(\gamma+1)}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right]^{1/2} \tag{12}$$

and the maximum theoretical specific impulse (Ref. 1) is given by

$$I_{sp} = \left(\frac{2\gamma RT_r}{g_o(\gamma - 1)}\right)^{1/2} \tag{13}$$

Substituting Eqs. (12) and (13) into Eq. (11) and rearranging

$$\omega_t = P_c A_t \left[\left(\frac{\gamma g_o}{RT_r}\right)\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right]^{1/2} \tag{14}$$

Since, for steady-state operation, the flow rate is constant, then

$$\omega_v = \omega_t \tag{15}$$

and

$$C_{dv}A_oP_o\left(\frac{P_c}{P_o}\right)^{1/\gamma}\left\{\left(\frac{2g_o}{RT_r}\right)\left(\frac{\gamma}{\gamma-1}\right)\left[1-\left(\frac{P_c}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2}$$

$$= A_tP_c\left[\left(\frac{\gamma g_o}{RT_r}\right)\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right]^{1/2} \tag{16}$$

Solving Eq. (16) for P_c, the valve chamber pressure is

$$\left(\frac{P_c}{P_o}\right)^{\frac{2-2\gamma}{\gamma}} - \left(\frac{P_c}{P_o}\right)^{\frac{1-\gamma}{\gamma}} - CPC = 0 = f(P_c) \tag{17}$$

where

$$CPC = \left[\left(\frac{\gamma-1}{2}\right)\left(\frac{A_t}{A_oC_{dv}}\right)^2\left(\frac{\gamma+1}{2}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right] \tag{18}$$

With a digital computer, a convenient method of solving nonlinear algebraic or transcendental equations to any degree of accuracy required is by the Newton-Raphson iteration method (Ref. 2) where

$$(P_c)_{n+1} = (P_c)_n - \left(\frac{f(P_c)}{\partial f(P_c)}\right)_n \tag{19}$$

The derivative of $f(P_c)$ is

$$\partial f(P_c) = \left[\left(\frac{2-2\gamma}{\gamma}\right)P_o^{\left(\frac{2\gamma-2}{\gamma}\right)}P_c^{\left(\frac{2-3\gamma}{\gamma}\right)}\right]$$

$$-\left[\left(\frac{1-\gamma}{\gamma}\right)P_c^{\left(\frac{\gamma-1}{\gamma}\right)}P_c^{\left(\frac{1-2\gamma}{\gamma}\right)}\right] \tag{20}$$

With the determination of P_c, the maximum theoretical thrust from the system can now be calculated from Eq. (12), given the dimensions of the valve and nozzle, the properties of the propellant at the inlet, and the ambient pressure. From this maximum thrust, valve losses in the nozzle are substracted for: (1) boundary layer effects, (2) nonparallel exit flow, and (3) partial flow expansion. For the steady-state case, the estimation of these losses is based on the internal memorandum by Bain Dayman, Jr. (see footnote 1, page 4).

For miniature nozzles of the sizes discussed in this report, the boundary layer thickness can be on the order of ½ of the nozzle geometric exit radius. Therefore, the momentum loss in the boundary layer is an appreciable fraction of the nozzle thrust, and must be considered when calculating the expected thrust. A simplified approach assumes that the various boundary layer parameters at the nozzle exit are the same as the boundary layer parameters on a flat plate. This involves the following assumptions:

(1) No boundary layer in the nozzle throat region.

(2) Laminar boundary layer.

(3) Adiabatic wall (no heat transfer).

(4) Flat plate length of ℓ.

(5) Uniform flow over flat plate at conditions (Mach number and pressure) of core flow at nozzle exit.

(6) Permissible to calculate various boundary layer thicknesses and areas as if the thicknesses were small compared to the nozzle geometric exit radius.

The relationship between exit Mach number (M_E) for sonic conditions at the throat (Ref. 3) is as follows:

$$\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} M_E\left[1+\frac{(\gamma-1)}{2}M_E^2\right]^{-\left(\frac{\gamma+1}{2(\gamma-1)}\right)}$$

$$-\left[\frac{A_e}{A_t}\right]^{-1}_{\text{aero}} = 0 = f(M_E) \tag{21}$$

Again, this equation is solved with the computer using the Newton-Raphson iteration method where

$$(M_E)_{n+1} = (M_E)_n - \left[\frac{f(M_E)}{\partial f(M_E)}\right]_n \tag{22}$$

The derivative of $f(M_E)$ is

$$\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left[1+\frac{\gamma-1}{2}M_E^2\right]^{\frac{-(\gamma+1)}{2(\gamma-1)}} - \left(\frac{\gamma+1}{2}\right)^{\frac{3\gamma-1}{2(\gamma-1)}} M_E^2\left[1+\frac{\gamma-1}{2}M_E^2\right]^{\frac{1-3\gamma}{2(\gamma-1)}} = \partial f(M_E) \tag{23}$$

The initial value of the aerodynamic nozzle area ratio, $(A_e/A_t)_{aero}$, used in the iteration is set equal to ½ the geometric nozzle area ratio. With the exit Mach number and corresponding value of $(A_e/A_t)_{aero}$, which satisfies Eq. (21)

$$f(M_E) =$$

now determined, the boundary layer thickness associated with that value of M_E can be found. The exit Reynolds number, R#, is (Ref. 3) expressed by

$$R\# = \frac{12P_oLM_E}{\mu_o}\left(\frac{\gamma}{(\gamma-1)C_vT_k}\right)^{1/2}\left(\frac{T_R}{T_E}\right)^{\frac{\gamma-2}{\gamma-1}} \times \left[\frac{T_E+198.6}{T_R+198.6}\right] \tag{24}$$

where (Ref. 3)

$$\mu_o = 2.27\times10^{-8}\frac{T_R^{3/2}}{T_R+198.6} \tag{25}$$

and

$$\frac{T_R}{T_E} = 1+\frac{\gamma-1}{2}M_E^2 \tag{26}$$

The boundary layer momentum thickness is

$$\delta = \frac{0.645L}{(R\#)^{1/2}} \tag{27}$$

The relationship between boundary layer momentum thickness and displacement thickness (δ^*/δ) as a function of Mach number was determined from Ref. 4.

Data points obtained from Ref. 4 were plotted and a least-squares curve fitting computer program used to obtain the following best fit equations (see Appendix B):

$$\frac{\delta^*}{\delta} = -0.00022M_E^6 + 0.00671M_E^5 - 0.07610M_E^4 + 0.39770M_E^3 - 0.30876M_E^2 + 0.99230M_E + 2.28324 \qquad 0 < M_E < 6.5 \tag{28a}$$

$$\frac{\delta^*}{\delta} = 8.6M_E - 25.9 \qquad 6.5 < M_E < 7.5 \tag{28b}$$

$$\frac{\delta^*}{\delta} = 10.0M_E - 36.4 \qquad 7.5 < M_E < 9 \tag{28c}$$

$$\frac{\delta^*}{\delta} = 10.9M_E - 44.4 \qquad 9.0M_E < 10 \tag{28d}$$

With the determination of the boundary layer displacement thickness, the effective aerodynamic nozzle exit radius is

$$(R_E)_{eff} = (R_E)_{geo} - \delta^* \tag{29}$$

The new aerodynamic nozzle area ratio is

$$\left(\frac{A_e}{A_t}\right)_{aero} = \left[\frac{(R_E)_{eff}}{R_T}\right]^2 \tag{30}$$

This new ratio is next compared with the ratio value used in Eq. (21), and Eqs. 21 through 30 repeated using the equation

$$\left[\left(\frac{A_e}{A_t}\right)_{aero}\right]_{n+1} = \frac{\left[\left(\frac{A_e}{A_t}\right)_{aero}\right]_{n-1} + \left[\left(\frac{A_e}{A_t}\right)_{aero}\right]_n}{2} \tag{31}$$

until

$$\left|\left[\left(\frac{A_t}{A_e}\right)_{aero}\right]_n - \left[\left(\frac{A_e}{A_t}\right)_{aero}\right]_{n-1}\right| \le \epsilon_3 \tag{32}$$

where ϵ_3 is the degree of accuracy required (0.001 in the se considered).

The ratio of thrust boundary layer loss subtracted from the maximum theoretical thrust to the maximum theoretical thrust is expressed by (see footnote 1, page 4):

$$L_\delta = \frac{2\delta(R_{E\text{-}geo} - \delta/2)}{(R_{E\text{-}geo} - \delta^*)^2} \tag{33}$$

The basic thrust equation for a nozzle operating in a vacuum can be written as

$$F = mV_E + P_E\,(A_e)_{\text{aero}} \tag{34}$$

where V_E is the mass-velocity vector parallel to the thrust axis. In the case of a conical nozzle, the exit velocities have both radial and axial components. The effective average exit velocity along the thrust axis is

$$(V_E)_{eff} = \frac{V_E}{2}\,[1 + \cos\,(\sigma)_{eff}] \tag{35}$$

where

$$\text{Cos}\,(\sigma)_{eff} = \frac{\ell}{[\ell^2 + (R_E)^2_{eff}]^{1/2}} \tag{36}$$

Therefore, the corresponding loss ratio is

$$L_p = \frac{F(V_E) - F(V_E)_{eff}}{F(V_E)} \tag{37a}$$

$$L_p = \frac{\dfrac{\omega_v V_E}{g_o} + P_E(A_e)_{\text{aero}} - \dfrac{\omega_v (V_E)_{eff}}{g_o} + P_E(A_e)_{\text{aero}}}{\left[\dfrac{\omega_v V_E}{g_o} + P_E(A_e)_{\text{aero}}\right]} \tag{37b}$$

$$L_p = \frac{1 - \dfrac{1}{2}(1 + \cos\,(\sigma)_{eff})}{1 + \dfrac{P_E(A_e)_{\text{aero}} g_o}{\omega_v C_E M_E}} \tag{37c}$$

where

$$C_E M_E = V_E \tag{38}$$

and

$$P_E = P_o\left(1 + \frac{\gamma - 1}{2} M_E^2\right)^{-\gamma/(\gamma-1)} \tag{39}$$

An additional thrust loss results from the flow having a pressure at the nozzle exit when the nozzle itself is operating in a vacuum (i.e., flow not fully expanded). This loss ratio is given by

$$L_n = \frac{F_{\max} - F_n}{F_{\max}} \tag{40}$$

for

$$F_n = P_c A_t C_f \tag{41}$$

where (see Ref. 5)

$$C_f = \left\{\left(\frac{2\gamma^2}{\gamma - 1}\right)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1 - \left(\frac{P_E}{P_c}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]\right\}^{1/2} + \frac{(P_E - P_A)}{P_c}\left(\frac{A_e}{A_t}\right)_{\text{aero}} \tag{42}$$

for

$$P_A = P_E = 0 \qquad F_n = F_{\max}$$

$$F_{\max} = P_c A_t\left[\left(\frac{2\gamma^2}{\gamma - 1}\right)\left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right]^{1/2} \tag{43}$$

The solution to Eq. (40) can be determined by combining Eqs. (41), (42), and (43). The total thrust loss ratio through the nozzle can be expressed as

$$L_t = 1 - [(1 - L_\delta)\,(1 - L_p)\,(1 - L_n)] \tag{44}$$

Therefore, the net thrust produced by the reaction jet is

$$F_{\text{net}} = F_{\max}\,(1 - L_t)$$

The flow chart and the 1620 computer program utilizing these equations to determine net thrust are presented in Appendix C. The list prints of the programs utilized to plot Figs. 5 through 10 are contained in Appendix D.

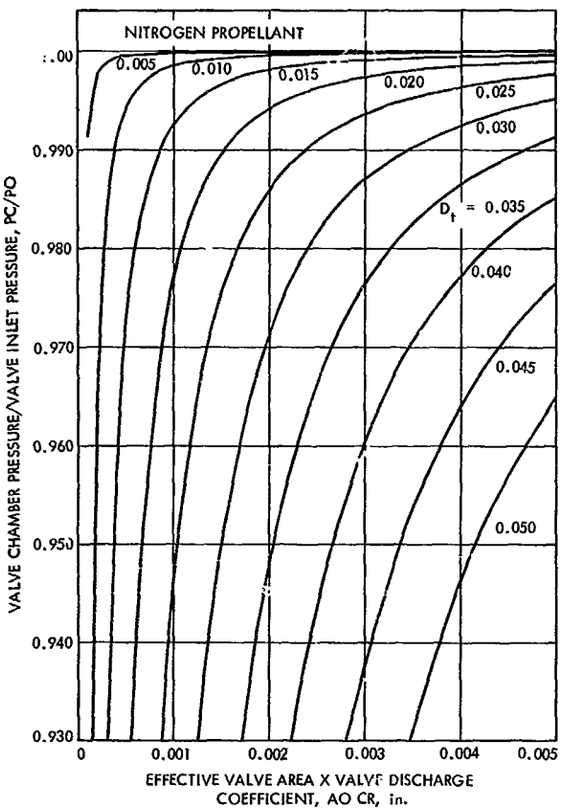


Fig. 5. Valve pressure ratio

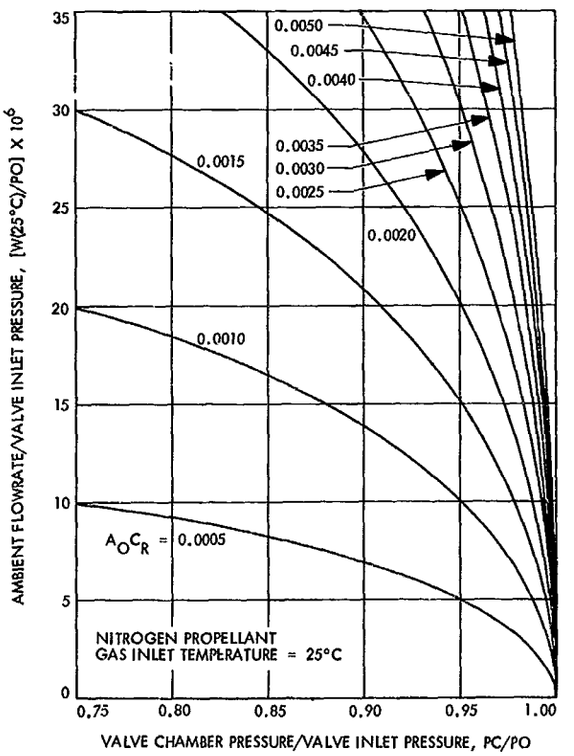


Fig. 6. Flow rate vs chamber pressure ratio

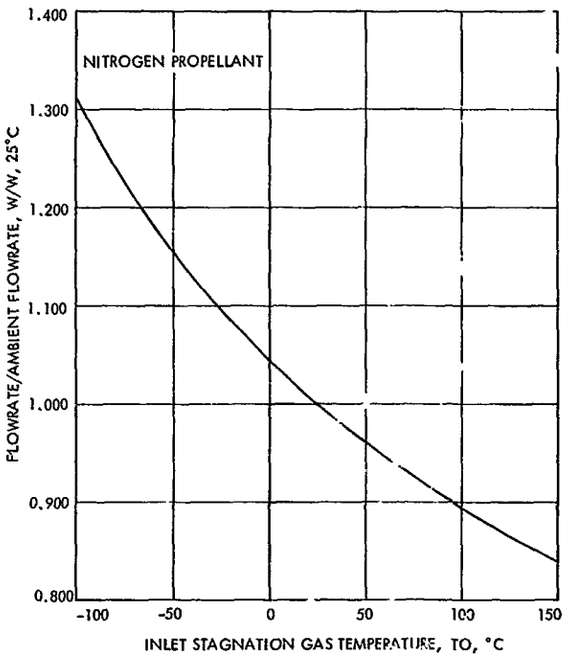


Fig. 7. Flow rate ratio vs temperature

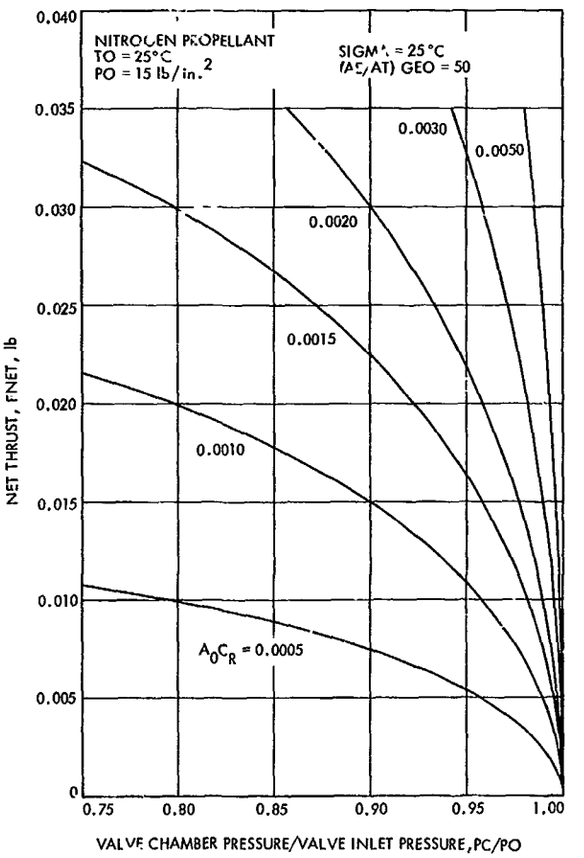


Fig. 8. Net thrust vs pressure ratio

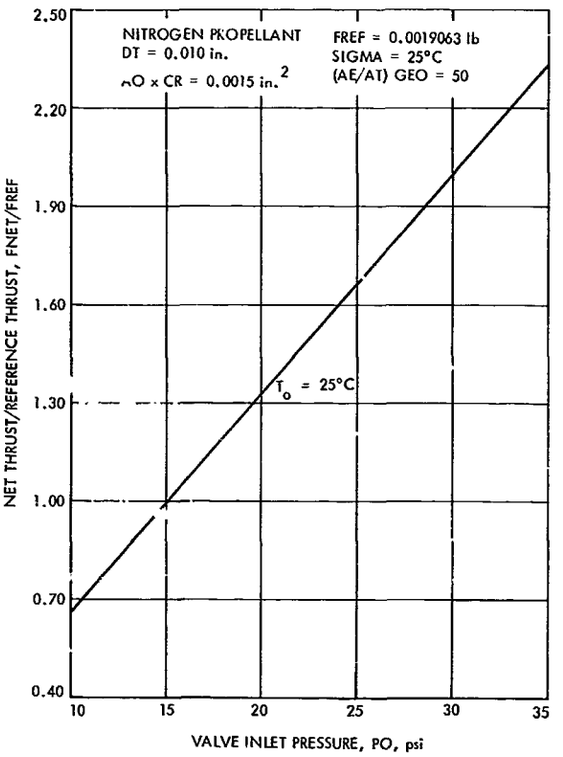


Fig. 9. Net thrust vs inlet pressure

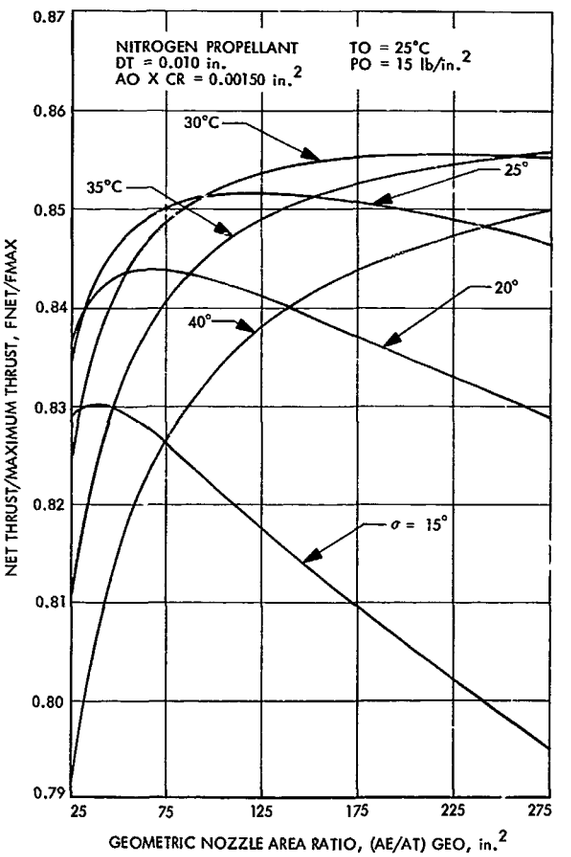


Fig. 10. Net thrust vs nozzle area ratio

III. Evaluation of Graphs

With the formulation of the equations expressed in Section II, a significant analytical tool is realized for the prediction of thruster steady-state performance. The analysis requires the following input data:

(1) Valve and nozzle geometries.

(2) Gas reservoir conditions.

(3) Valve orifice discharge coefficient.

(4) Ambient conditions.

To demonstrate the capabilities of this analysis, a series of parametric plots was generated using the IBM 1620 II Data Processing System augmented by the IBM 1627 Plotter. The following set of reference conditions, approximating *Mariner IV* parameters, has been used for convenience:

$$P_o = 15 \text{ lb/in.}^2$$

$$T_o = 25°\text{C}$$

$$A_oC_r = 0.0015 \text{ in.}^2$$

$$D_t = 0.010 \text{ in.}$$

$$(A_e/A_t)_{geo} = 50$$

$$\sigma = 25 \text{ deg}$$

$$P_{-1} = 0 \text{ lb/in.}^2$$

$$\gamma = 1.401$$

$$F_{ref} = 0.00191 \text{ lb}$$

$$F_{max} = 0.00213 \text{ lb}$$

A value for the A_oC_r parameter is required to use the plot series. This factor involves determining the valve orifice area (A_o). The procedure is outlined in Appendix A for a typical ball valve. It is also necessary to input the valve orifice discharge coefficient (C_{dv}). The product of A_o and C_{dv} is A_oC_r. At present, this discharge coefficient is approximated because experimental values have not been obtained for a range of orifice and nozzle geometries.

The effect of A_oC_r on the ratio of chamber pressure to inlet pressure is shown in Fig. 5 for a range of nozzle throat diameters from 0.005 to 0.050 in.^{2} Figure 5 is plotted from Eq. (17). For a given inlet pressure, the chamber pressure increases (pressure drop decreases) as the downstream throat diameter increases and as A_oC_r increases.

Figure 6 illustrates the ratio of propellant weight flow rate at $T_o = 25°\text{C}$ to gas inlet pressure as a function of the pressure ratio previously determined from Fig. 5. It is apparent from this plot that the weight flow rate is inversely proportional to the pressure ratio for any given A_oC_r.

The effect of gas inlet temperatures ranging from -100 to 150°C on the weight flow rate is shown in Fig. 7. The flow rate is expressed as a ratio of the flow rate at a given temperature to the flow rate at 25°C. This ratio is inversely proportional to temperature. Figures 5, 6, and 7 thus establish a flow rate for any set of inlet conditions and valve-nozzle geometry.

The net steady-state thrust is shown in Fig. 8 as a function of the pressure ratio for a range of A_oC_r from 0.0005 to 0.005 in.^{2} and for $P_o = 15$ lb/in.^{2} As indicated in Fig. 5, an increase in nozzle throat diameter (D_t) for a constant A_oC_r results in a decrease in the chamber pressure for a constant P_o because, with a larger nozzle diameter, a greater percentage of the total pressure drop across the nozzle and valve in series occurs across the valve. This decrease in thrust, resulting from a decrease in chamber pressure, is offset, however, by the increase in thrust caused by the larger nozzle diameter. This relationship is indicated in Fig. 8 where the net thrust increases as the pressure ratio decreases (indicating increasing nozzle throat area) for a constant value of A_oC_r and P_o. If Fig. 8 had been plotted for constant values of nozzle throat diameter (D_t) rather than constant values of A_oC_r, it could be shown that net thrust increases as the nozzle throat diameter increases for constant values of A_oC_r and P_o. It should be noted that, in Fig. 8, the inlet temperature, the inlet pressure, the nozzle half-angle, and the nozzle geometric area ratio are set at the reference conditions.

Variations of the reference conditions generate the graphs in Figs. 9 and 10. Figure 9 shows the effect of increasing gas inlet pressure (P_o) on the ratio of calculated net thrust at the given P_o to net thrust at $P_o = 15$ lb/in.^{2} and $T_o = 25°\text{C}$ (i.e., reference thrust). A temperature range from -200 to 250°C is considered. The plots representing these two extremes of temperature are parallel to the plot for $T_o = 25°\text{C}$, the $-200°\text{C}$ value increasing net thrust by 0.525% and the 250°C value decreasing net thrust by 0.525%. The net thrust is therefore relatively insensitive to large changes in gas inlet temperature. Therefore, since the flow rate is inversely proportional to temperature, the specific impulse ($I_{sp} = F/\omega$) increases with increasing temperature as anticipated. The

above temperature range is believed to include most future planetary mission constraints.

The effects of nozzle skirt geometry become more evident in Fig. 10 where geometric nozzle area ratio and nozzle half-angle are considered for all other variables at reference conditions. The vertical axis of Fig. 10 is a ratio of the net thrust for the indicated value of half-angle and geometric area ratio to the maximum thrust for the reference conditions as given by Eq. (43). As such, Fig. 10 should be used mainly as an indication of the trend of the net thrust as a function of these two parameters. To determine the actual net thrust for conditions other than reference conditions, a computer run should be made (see Appendix C). In Fig. 10, it is apparent that an optimum nozzle area ratio exists for each half-angle; this optimum area ratio and the corresponding maximum net thrust for the given half-angle increase as the half-angle increases for values of A_e/A_t to 175. This trend indicates that values of A_e/A_t from 50 to 175 and of half-angle from 25 to 30 deg would be good design parameters.

IV. Conclusions and Recommendations

The theoretical analysis and associated parametric plots for steady-state thruster performance have been demonstrated. With the parametric plot series and associated computer programs, it is practical to predict weight flow rate and net thrust, given the nozzle geometry and gas condition inputs previously outlined. Conversely, given the appropriate mission requirements, thruster design requirements may be determined by applying the mathematical analysis.

As a verification of a portion of the analysis and its supporting assumptions, input data corresponding to the *Mariner IV* pitch-yaw and roll thrusters were used to predict steady-state thrust. These input data result from laboratory experimentation. The results are shown in Table 1.

Table 1. Comparison of steady-state thrust, computer and test data

	Net thrust test data, lb	Net thrust computed prediction, lb	Difference, %
Pitch-yaw	0.00225	0.00233	3.43
Roll	0.0040	0.00399	0.25

The close agreement presented in Table 1 indicates that, for values of the design parameters close to the *Mariner IV* data, the initial assumptions outlined previously to facilitate an analytical solution are valid. The test previously mentioned is the only attempt made by the authors to date to verify the graphical results presented in this report. In the absence of test verification, the authors anticipate a 10 to 20% spread in computer versus test results at the extremes of the design parameters. Tests will be conducted to substantiate these claims.

There are two major areas in the analytical derivations which could lead to major differences in net thrust values for computer versus actual test data. The first area is in the determination of the valve orifice discharge coefficient as a function of valve geometry and inlet gas conditions. The second area of concern is in the calculation of thrust losses, particularly losses caused by boundary layer buildup in the nozzle. A flat plate analogy was used to calculate boundary layer thickness. Since the task presented in this report was initiated, more accurate methods of predicting boundary layer losses in conical nozzles have become available. These were not incorporated into this report.

This analysis is restricted to a subsonic orifice in series with a sonic nozzle throat and separated by a chamber volume of approximately 0.2 cc. Cold nitrogen gas was assumed to be the propellant throughout the study; the capability for accommodating other gases within the computer series does exist. For some gases, a thrust loss caused by vapor condensation in the nozzle must be taken into account (Ref. 1). The analysis could also be extended to include the effect of heating the gas in the chamber (Ref. 6).

This report summarizes a first iteration attempt at providing an analytical and design tool to be used in fabricating valve-nozzle configurations to meet specific steady-state thrust requirements. As such, improvements can be made in future iterations. The following are recommendations for future effort on this program:

(1) Set up an experimental program and/or literature search to determine the valve orifice discharge coefficient as a function of valve geometry and inlet gas conditions.

(2) Incorporate into this program available information from recent literature on more accurate determination of boundary layer thicknesses in conical nozzles.

(3) Establish test apparatus to measure steady-state thrust for a variety of valve-nozzle configurations to verify the results presented in this report over the range of parameters considered. This effort is currently in progress to a limited extent.

(4) Compare the results of this report with recent literature published on similar efforts.

(5) Once the steady-state analysis has been updated and verified, initiate a similar type of analysis for transient response to determine thrust-time profiles, and thus, total impulse delivered for the attitude control gas jets.

(6) Perform similar analysis to study such areas as gases other than nitrogen, the possibility of heating the gas prior to expulsion, and valve configurations not considered in this report.

Appendix A

Valve Orifice Effective Area

A typical ball valve in the closed and open positions is shown in Fig. A-1. From these diagrams:

$$A_1 = (R_b^2 - R_s^2)^{1/2} \tag{A-1}$$

$$A_2 = A_1 + T_b \tag{A-2}$$

$$\phi_2 = \tan^{-1}(R_s/A_2) \tag{A-3}$$

$$\text{Sin}\,\phi_2 = R_s/(R_s^2 + A_2^2)^{1/2} \tag{A-4}$$

$$Q = \frac{R_s}{\text{Sin}\,\phi_2} - R_b \tag{A-5}$$

$$\frac{B}{R_b} = \frac{R_s}{R_b + Q} \text{ or } B = \frac{R_b R_s}{R_b + Q} \tag{A-6}$$

$$\frac{E}{R_b} = \frac{A_2}{R_b + Q} \text{ or } E = \frac{A_2 R_b}{R_b + Q} = \frac{BA_2}{R_s} \tag{A-7}$$

and

$$H = A_2 - E \tag{A-8}$$

The equation for the surface area of a truncated cone is

$$A_o = \pi(R_s + B)\left(H^2 + (R_s - B)^2\right)^{1/2} \tag{A-9}$$

Substituting Eqs. (A-6) and (A-8) into Eq. (A-9) and simplifying gives

$$A_o = \frac{\pi R_s T_b \left[2(R_b^2 - R_s^2)^{1/2} + T_b\right]}{\left[R_b^2 + T_b\left[2(R_b^2 - R_s^2)^{1/2}\right] + I_b^2\right]^{1/2}} \tag{A-10}$$

Figure A-2 illustrates the effective value orifice area for a range of ball travel from 0.002 to 0.012 in. using the *Mariner IV* values of ball and seat radius.

$$R_s = 0.066 \text{ in.}$$

$$R_b = 0.094 \text{ in.}$$

Equation (A-10) then becomes

$$A_o = \frac{(0.2073)(T_b)(0.134 + T_b)}{[0.008836 + T_b(0.134 + T_b)]^{1/2}} \tag{A-11}$$

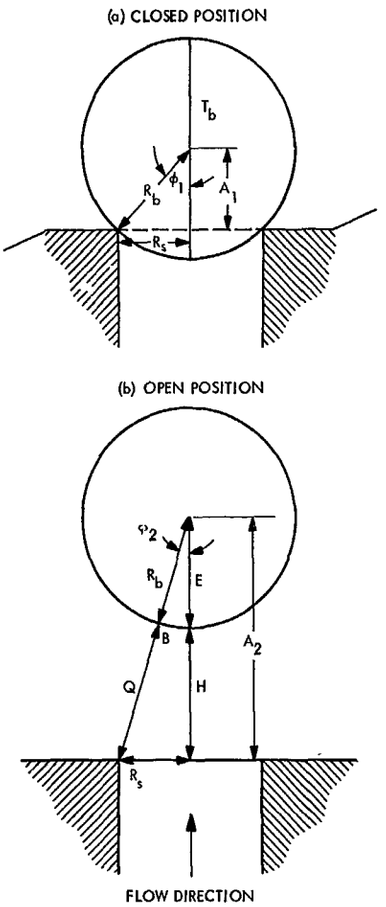


Fig. A-1. Ball valve operation diagram

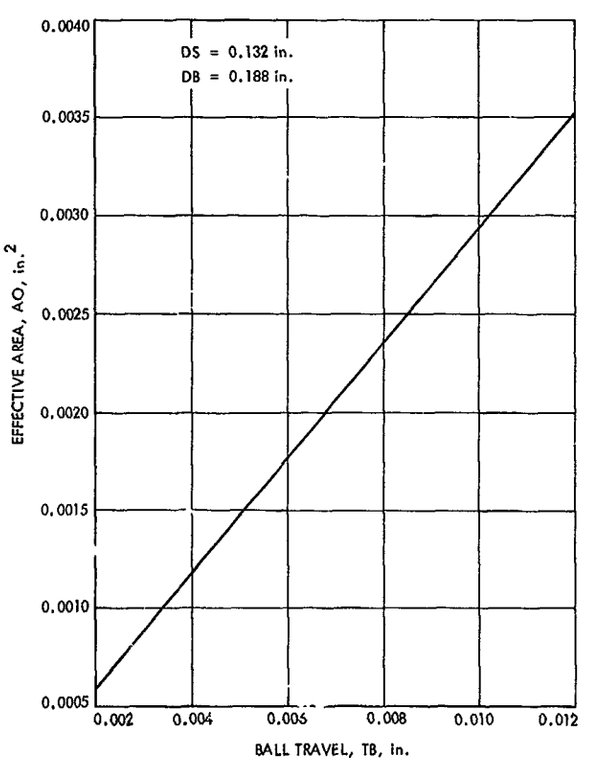


Fig. A-2. Ball valve effective orifice area

I. List Print for Fig. A-2

```
      DS=.132
      DB=.188
      PI=3.1416
      READ 1,TBMIN,TBMAX,TBLEN,TBINC,AOMIN,AOMAX,AOLEN,AOINC
    1 FORMAT(2F10.5,F5.1,F10.5,2F10.7,F5.1,F10.7)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.1)
      XMIN=TBMIN
      XMAX=TBMAX
      XLEN=TBLEN
      XINC=TBINC
      YMIN=AOMIN
      YMAX=AOMAX
      YLEN=AOLEN
      YINC=AOINC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 4 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    3 FORMAT(F6.3)
    4 DL=DL+1.
      DL=0.
      DO 6 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    5 FORMAT(F7.4)
    6 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,DB)
    7 FORMAT(4HDB =,F6.3,1X2HIN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,DS)
    8 FORMAT(4HDS =,F6.3,1X2HIN)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(0,0.1,0)
    9 FORMAT(2HTB)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
      CALL CHAR(0,0.2,0)
   10 FORMAT(33HBALL VALVE EFFECTIVE ORIFICE AREA)
      CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
     1C))/2.))
      CALL CHAR(0,0.1,1)
   11 FORMAT(2HAO)
      N1=11
      N2=N1-1
```

```
      FLON2=N2
      RB=DB/2.
      RS=DS/2.
      AOX=PI*(RS**2)
      PRINT 12,AOX
   12 FORMAT(5X12HSEAT AREA = ,E15.8,///)
      PRINT 13
   13 FORMAT(9X28HEFFECTIVE VALVE ORIFICE AREA,12X11HBALL TRAVEL,/,
     119X8HAO (IN2),25X5H(IN.),/)
      TB=TBMIN
      DO 22 I=1,N1
      A1=SQRTF((RB**2)-(RS**2))
      A2=A1+TB
      PHI2=ATANF(RS/A2)
      Q=(RS/SINF(PHI2))-RB
      B=RB*RS/(RB+Q)
      E=A2*B/RS
      H=A2-E
      AO=PI*(RS+B)*SQRTF((H**2)+((RS-B)**2))
      IF(AO-AOX)15,15,14
   14 AO=AOX
   15 PRINT 16,AO,TB
   16 FORMAT(14X,E15.8,21X,F7.4)
      IF(AO-AOMIN)21,21,17
   17 IF(AOMAX-AO)21,21,18
   18 IF(I-2)20,19,20
   19 PAUSE
   20 CALL PLOT(90,TB,AO)
   21 TB=TB+((TBMAX-TBMIN)/FLON2)
   22 CONTINUE
      CALL PLOT(99)
      END
```

II. Output Data from Computer Program for Effective Valve Orifice Area

SEAT AREA = .13684809E-01 IN^2

EFFECTIVE VALVE ORIFICE AREA AO (IN2)	BALL TRAVEL (IN.)
.59037808E-03	.0020
.88536072E-03	.0030
.11801498E-02	.0040
.14747079E-02	.0050
.17689989E-02	.0060
.20629836E-02	.0070
.23566464E-02	.0080
.26499431E-02	.0090
.29428477E-02	.0100
.32353455E-02	.0110
.35274030E-02	.0120

Appendix B

Boundary Layer Thicknesses Versus Mach Number

The values of the boundary layer displacement and momentum thickness were taken from Ref. 4 for Mach numbers ranging from 0.4 to 5. The values of boundary layer thicknesses for Mach numbers ranging from 5 to 10 were obtained through personal conversation with Leslie Mack, the author of Ref. 4. These values are presented in Table B-1.

For Mach numbers between 0 and 6.5, a standard least-squares curve fitting program for polynomials up to tenth order was used to determine the equation which best fits the data points in Table B-1. The resulting equation used in this analysis is

$$\frac{\delta^*}{\delta} = -0.00022\,M_E^6 + 0.00671\,M_E^5 - 0.07610\,M_E^4 + 0.39770\,M_E^3 - 0.30876\,M_E^2 + 0.99230\,M_E + 2.28324 \qquad 0 < M_E < 6.5 \qquad \text{(B-1)}$$

For Mach numbers between 6.5 and 10, three straight line segment were used to best fit the data points. These equations are as follows:

$$\frac{\delta^*}{\delta} = 8.6\,M_E - 25.9 \qquad 6.5 < M_E < 7.5 \qquad \text{(B-2)}$$

$$\frac{\delta^*}{\delta} = 10.0\,M_E - 36.4 \qquad 7.5 < M_E < 9 \qquad \text{(B-3)}$$

$$\frac{\delta^*}{\delta} = 10.9\,M_E - 44.4 \qquad 9 < M_E < 10 \qquad \text{(B-4)}$$

A plot of the data points and the fitted curves is shown in Fig. B-1.

Table B-1. Values of boundary layer thicknesses[a]

M_e	$\delta^* (R\#_{\infty})^{1/2}/X^*$	$\delta (R\#_{\infty})^{1/2}/X^*$	δ^*/δ
0.4	1.7880	0.66225	
0.8	1.9837	0.65837	
1.2	2.3104	0.65316	
1.3	2.4128	0.65182	
1.4	2.5235	0.65050	
1.6	2.7695	0.64799	
1.8	3.0495	0.64573	
2.0	3.3638	0.64388	
2.2	3.7128	0.64244	
2.4	4.0986	0.64150	
2.6	4.5200	0.64102	
2.7	4.7450	0.64100	
2.8	4.9791	0.64104	
3.0	5.4767	0.64155	
3.2	6.0116	0.64228	
3.4	6.5813	0.64294	
3.6	7.1855	0.64354	
3.8	7.8244	0.64403	
4.0	8.4977	0.64448	
4.2	9.2058	0.64488	
4.4	9.9480	0.64523	
4.5	10.3322	0.64539	
4.6	10.7248	0.64555	
4.8	11.5360	0.64583	
5.0	12.3813	0.64609	
5.5			22.6
6.0			26.3
6.5			30.0
7.0			34.0
7.5			38.6
8.0			43.2
8.5			48.6
9.0			53.7
9.5			59.2
10.0			64.6

[a]The values in this table are for air at a stagnation temperature of 100°F.

M_e = Mach number.

δ^* = boundary layer displacement thickness.

δ = boundary layer momentum thickness.

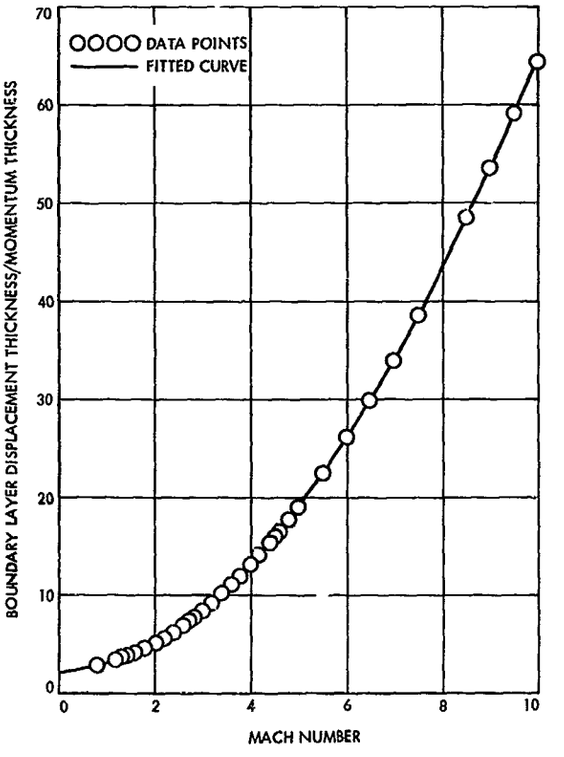


Fig. B-1. Mach number vs boundary layer

Appendix C

Detailed Description of Net Thrust Prediction Program

The equations resulting from the analytical derivation were programmed for the IBM 1620 II Data Processing System augmented by the IBM 1627 Plotter using Fortran language. A detailed flow chart of the basic program is included both to indicate the sequence of mathematical operations and to aid those not familiar with Fortran in following the program. The flow chart has been keyed to the statement numbers in the basic program. Portions of this basic program were used to produce the programs (Appendix D) needed to generate the parametric curves for Figs. 5 through 10. Also, list prints of the output for inputs typical of *Mariner IV* operating parameters (see values used as listed in parentheses after card inputs below) are included in this appendix to indicate the output format. The inputs to the program are read in on three input cards according to the program statements 1, 5, and 7, respectively, as follows:

(1) Card 1 (Statement 1)

Read in:

MAX1 maximum number of chamber pressure iterations–(30)

MAX2 maximum number of Mach number iterations–(30)

MAX3 maximum number of boundary layer iterations–(30)

ESP1 chamber pressure iteration accuracy value–(0.0001)

ESP2 Mach number iteration accuracy value–(0.0001)

ESP3 boundary layer iteration accuracy value (0.01)

(2) Card 2 (Statement 5)

Read in:

CDV valve orifice discharge coefficient–(0.3478)

TB valve ball travel from seat face (in.)–(0.0085)

TO inlet gas temperature (°C)–(25)

DB valve orifice ball diameter (in.)–(0.188)

DS valve orifice seat diameter (in.)–(0.132)

ARTGEO geometric nozzle area ratio (in.^{2})–(260.5)

CV specific heat at constant volume (ft^2/s^2-°R)–(4290)

SIGDEG nozzle exit half angle (deg)–(25)

GAMMA ratio of specific heats (1.401)

(3) Card 3 (Statement 7)

Read in:

R gas constant (in.-lb$_f$/lb$_m$-°R)–(661.92)

PA ambient pressure (lb/in.^{2})–(0)

PO valve inlet pressure (lb/in.^{2})–(15)

PCINIT initial chamber pressure iteration value (lb/in.^{2})–(14.9)

DT nozzle throat diameter (in.)–(0.0113 and 0.0147)

CNINIT initial nozzle exit Mach number iteration value–(6)

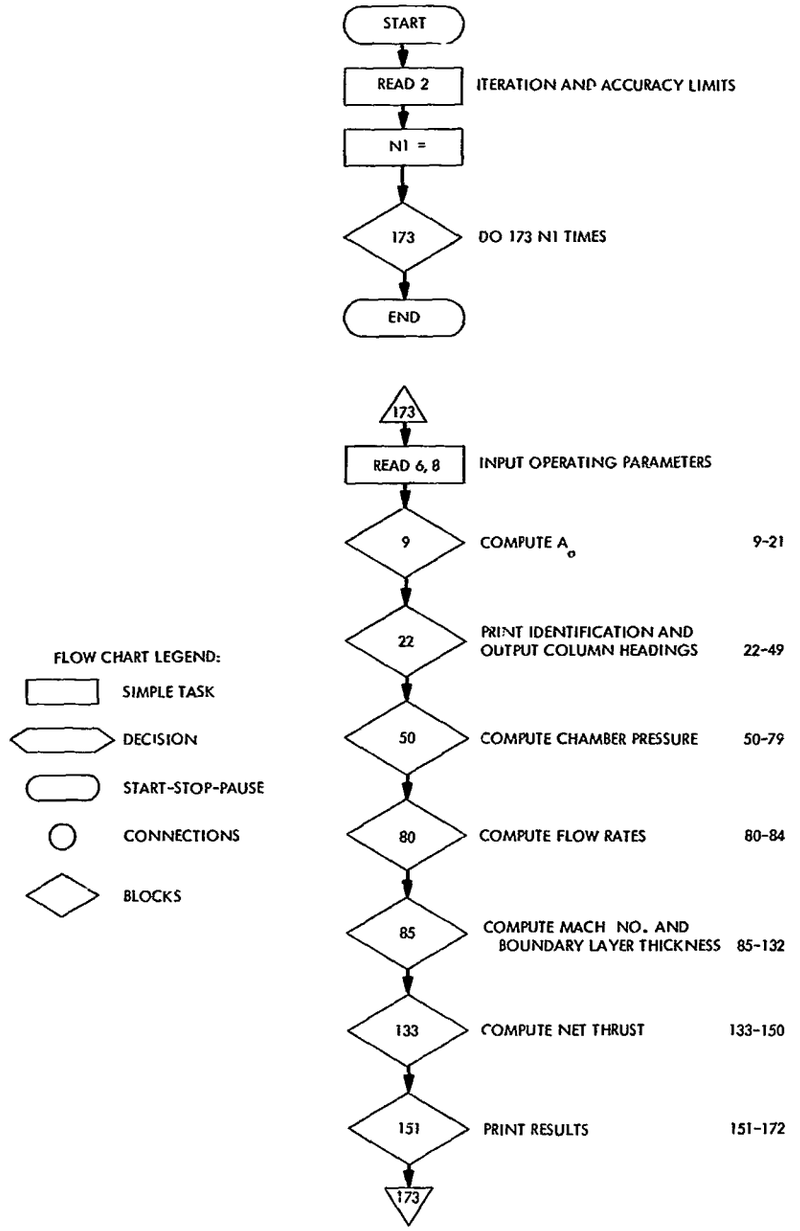
PI 3.1416

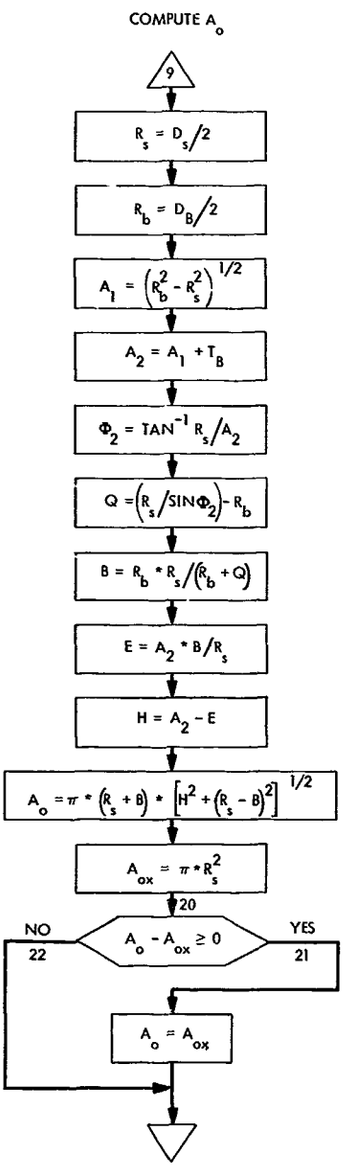
GO acceleration of gravity (in./s^2)–386.068

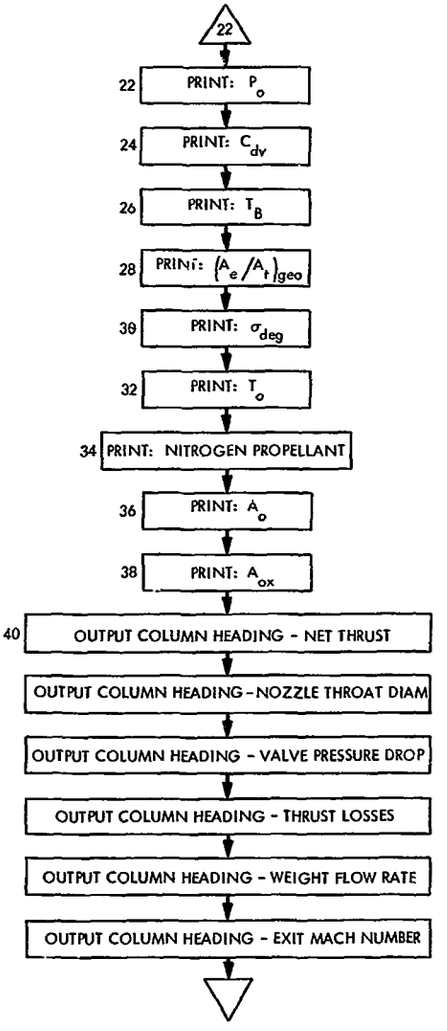
The basic program is set up to completely recycle for each set of initial values of the operating parameters read in on Cards 2 and 3. The number of times Cards 2 and 3 are read in is governed by the value of the variable N1.

The flow chart and list print of the basic program with *Mariner IV* output follow.

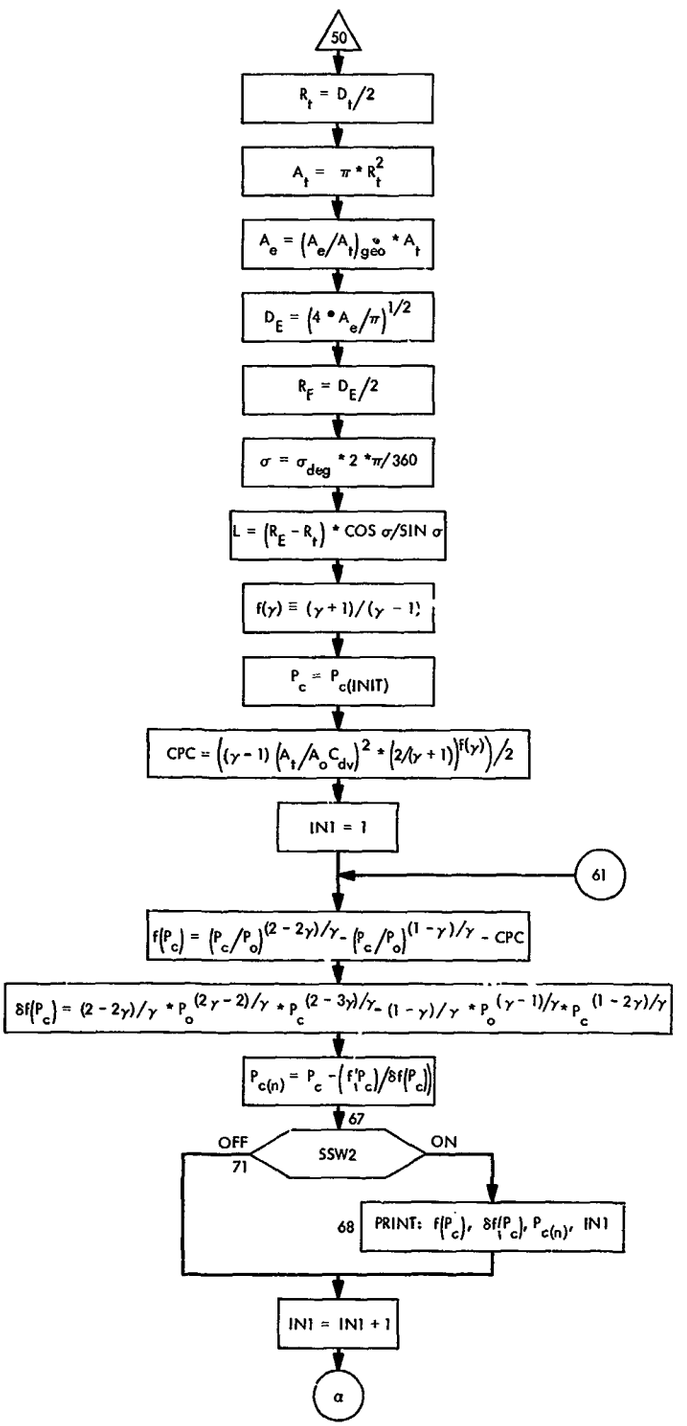
I. Flow Chart for Net Steady-State Thrust Prediction Program

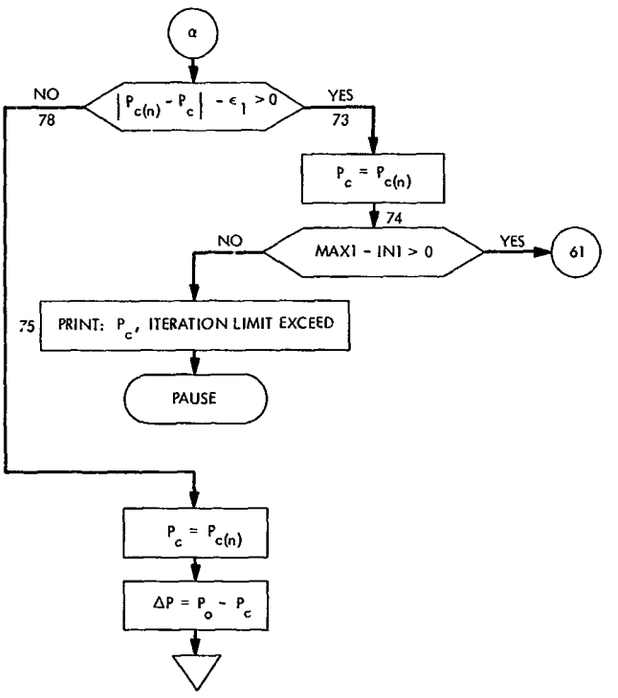



COMPUTE A_o
9
$R_s = D_s/2$
$R_b = D_B/2$
$A_1 = \left(R_b^2 - R_s^2\right)^{1/2}$
$A_2 = A_1 + T_B$
$\Phi_2 = TAN^{-1} R_s/A_2$
$Q = \left(R_s/SIN\Phi_2\right) - R_b$
$B = R_b * R_s/\left(R_b + Q\right)$
$E = A_2 * B/R_s$
$H = A_2 - E$
$A_o = \pi * \left(R_s + B\right) * \left[H^2 + \left(R_s - B\right)^2\right]^{1/2}$
$A_{ox} = \pi * R_s^2$
20
NO
22
$A_o - A_{ox} \geq 0$
YES
21
$A_o = A_{ox}$

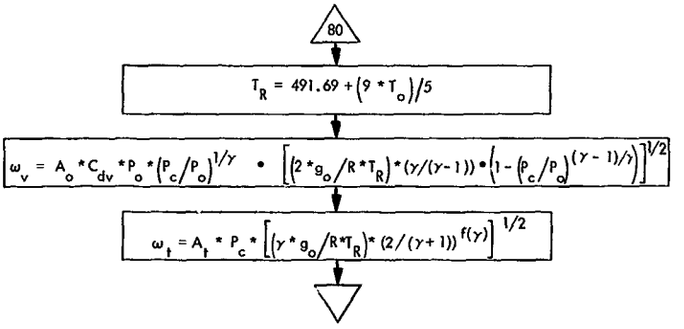

22
22 PRINT: P_o
24 PRINT: C_{dv}
26 PRINT: T_B
28 PRINT: $(A_e/A_t)_{geo}$
30 PRINT: σ_{deg}
32 PRINT: T_o
34 PRINT: NITROGEN PROPELLANT
36 PRINT: A_o
38 PRINT: A_{ox}
40 OUTPUT COLUMN HEADING - NET THRUST
OUTPUT COLUMN HEADING - NOZZLE THROAT DIAM
OUTPUT COLUMN HEADING - VALVE PRESSURE DROP
OUTPUT COLUMN HEADING - THRUST LOSSES
OUTPUT COLUMN HEADING - WEIGHT FLOW RATE
OUTPUT COLUMN HEADING - EXIT MACH NUMBER

COMPUTE CHAMBER PRESSURE

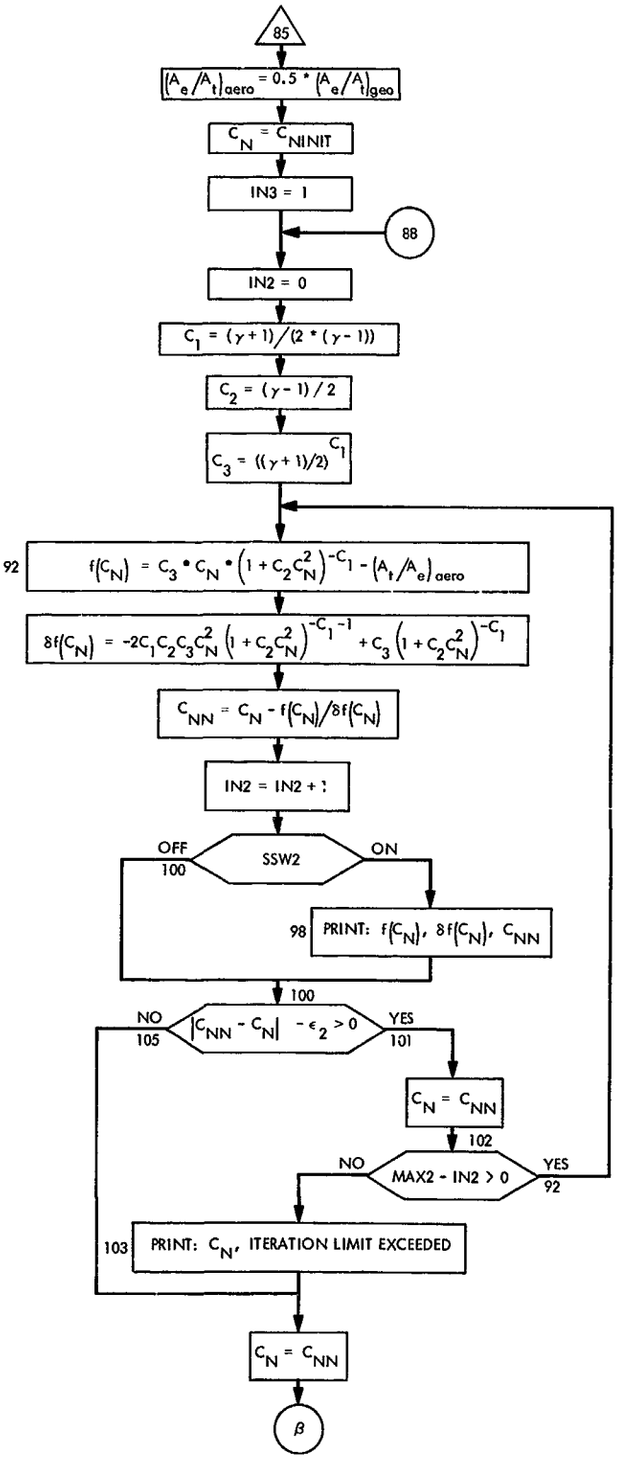

50
$R_t = D_t/2$
$A_t = \pi * R_t^2$
$A_e = \left(A_e/A_t\right)_{geo} * A_t$
$D_E = \left(4 * A_e/\pi\right)^{1/2}$
$R_F = D_E/2$
$\sigma = \sigma_{deg} * 2 * \pi/360$
$L = \left(R_E - R_t\right) * COS\ \sigma/SIN\ \sigma$
$f(\gamma) \equiv (\gamma + 1)/(\gamma - 1)$
$P_c = P_{c(INIT)}$
$CPC = \left((\gamma - 1)\left(A_t/A_o C_{dv}\right)^2 * \left(2/(\gamma + 1)\right)^{f(\gamma)}\right)/2$
IN1 = 1
61
$f(P_c) = \left(P_c/P_o\right)^{(2-2\gamma)/\gamma} - \left(P_c/P_o\right)^{(1-\gamma)/\gamma} - CPC$
$\delta f(P_c) = (2-2\gamma)/\gamma * P_o^{(2\gamma-2)/\gamma} * P_c^{(2-3\gamma)/\gamma} - (1-\gamma)/\gamma * P_o^{(\gamma-1)/\gamma} * P_c^{(1-2\gamma)/\gamma}$
$P_{c(n)} = P_c - \left(f(P_c)/\delta f(P_c)\right)$
67
OFF
SSW2
ON
71
68
PRINT: $f(P_c)$, $\delta f(P_c)$, $P_{c(n)}$, IN1
IN1 = IN1 + 1
α

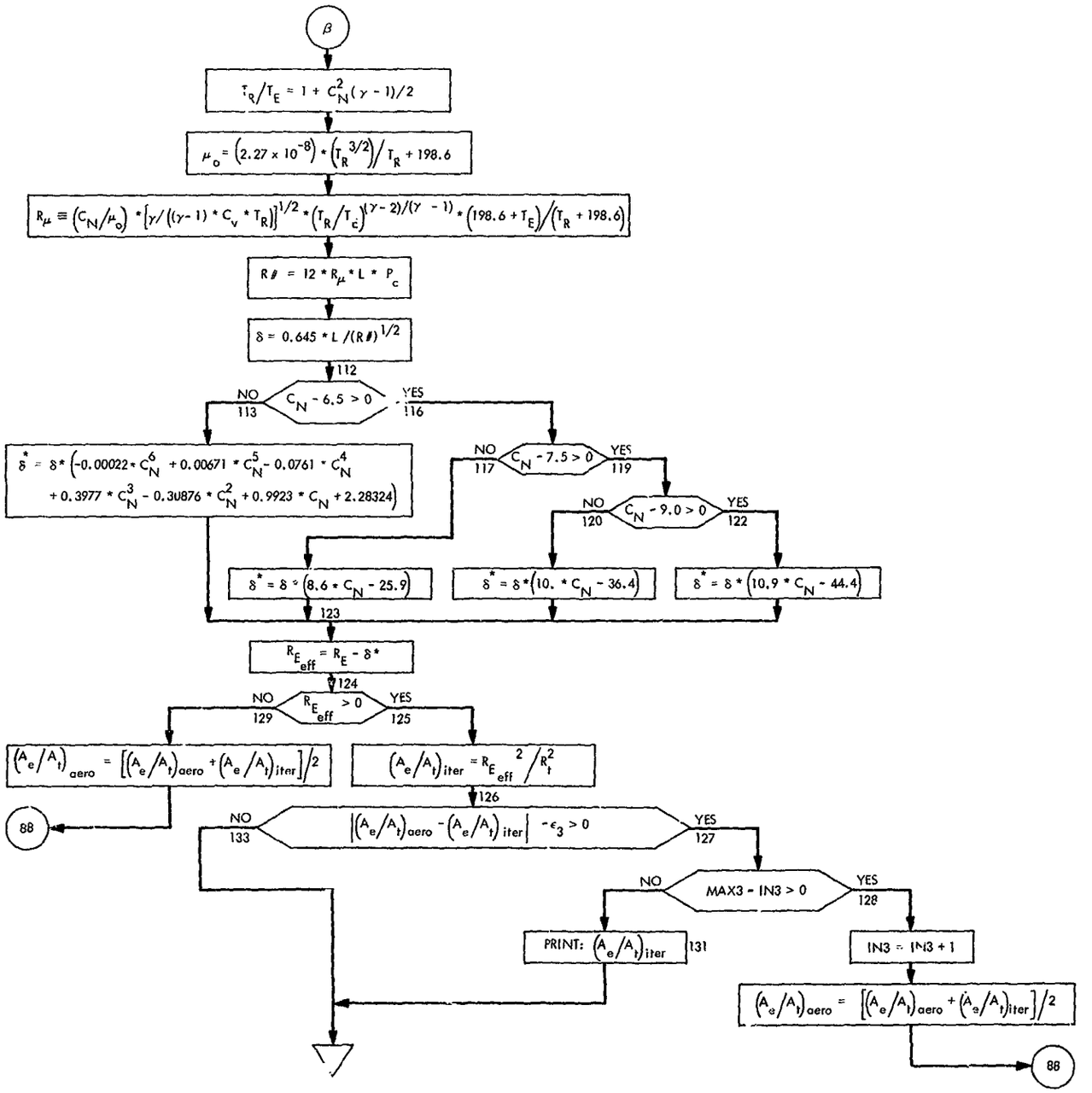


COMPUTE FLOW RATES

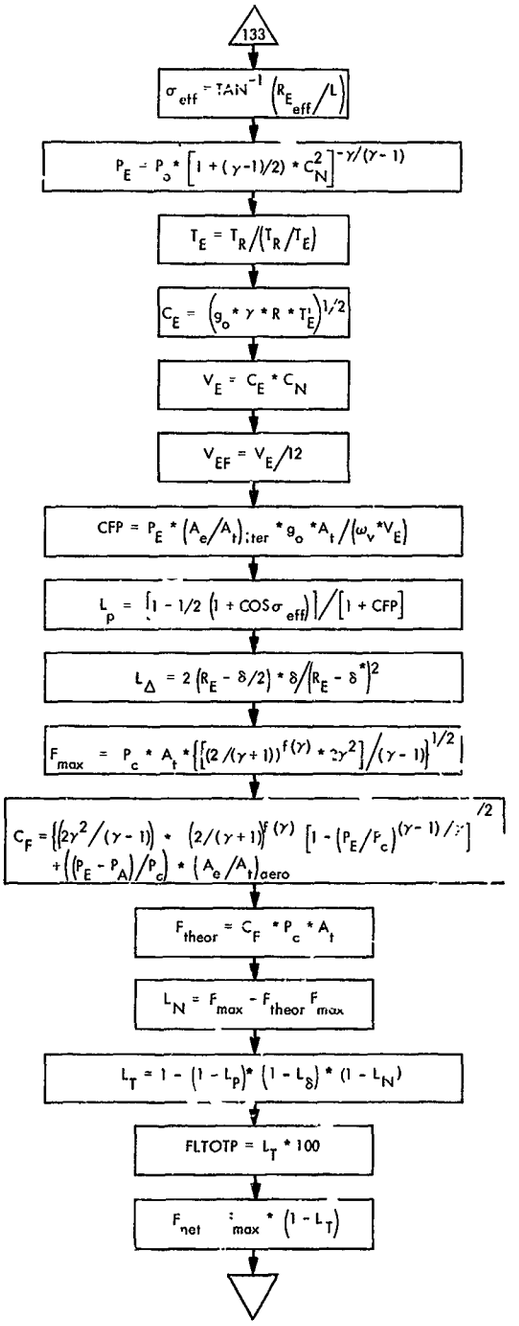

80
$T_R = 491.69 + (9 * T_o)/5$
$\omega_v = A_o * C_{dv} * P_o * (P_c/P_o)^{1/\gamma} \cdot \left[(2 * g_o/R * T_R) * (\gamma/(\gamma-1)) \cdot (1 - (P_c/P_o)^{(\gamma-1)/\gamma})\right]^{1/2}$
$\omega_t = A_t * P_c * \left[(\gamma * g_o/R * T_R) * (2/(\gamma+1))^{f(\gamma)}\right]^{1/2}$

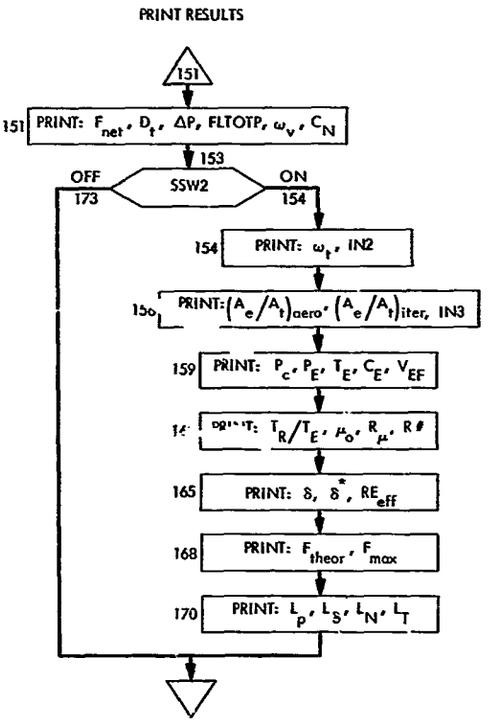
COMPUTE MACH NO. AND BOUNDARY LAYER THICKNESS




β
$T_R/T_E = 1 + C_N^2(\gamma - 1)/2$
$\mu_o = (2.27 \times 10^{-8}) * (T_R^{3/2}) / (T_R + 198.6)$
$R_\mu \equiv (C_N/\mu_o) * [\gamma/((\gamma-1) * C_v * T_R)]^{1/2} * (T_R/T_c)^{(\gamma-2)/(\gamma-1)} * (198.6 + T_E)/(T_R + 198.6)$
$R\# = 12 * R_\mu * L * P_c$
$\delta = 0.645 * L/(R\#)^{1/2}$
112
NO
$C_N - 6.5 > 0$
YES
113
116
$\delta^* = \delta * (-0.00022 * C_N^6 + 0.00671 * C_N^5 - 0.0761 * C_N^4 + 0.3977 * C_N^3 - 0.30876 * C_N^2 + 0.9923 * C_N + 2.28324)$
NO
$C_N - 7.5 > 0$
YES
117
119
NO
$C_N - 9.0 > 0$
YES
120
122
$\delta^* = \delta * (8.6 * C_N - 25.9)$
$\delta^* = \delta * (10. * C_N - 36.4)$
$\delta^* = \delta * (10.9 * C_N - 44.4)$
123
$R_{E_{eff}} = R_E - \delta^*$
124
NO
$R_{E_{eff}} > 0$
YES
129
125
$(A_e/A_t)_{aero} = [(A_e/A_t)_{aero} + (A_e/A_t)_{iter}]/2$
$(A_e/A_t)_{iter} = R_{E_{eff}}^2 / R_t^2$
126
88
NO
$|(A_e/A_t)_{aero} - (A_e/A_t)_{iter}| - \epsilon_3 > 0$
YES
133
127
NO
MAX3 - IN3 > 0
YES
128
PRINT: $(A_e/A_t)_{iter}$
131
IN3 = IN3 + 1
$(A_e/A_t)_{aero} = [(A_e/A_t)_{aero} + (A_e/A_t)_{iter}]/2$
88

COMPUTE NET THRUST


133
$\sigma_{eff} = TAN^{-1}\left(R_{E_{eff}}/L\right)$
$P_E = P_o * \left[1 + (\gamma-1)/2) * C_N^2\right]^{-\gamma/(\gamma-1)}$
$T_E = T_R/\left(T_R/T_E\right)$
$C_E = \left(g_o * \gamma * R * T_E\right)^{1/2}$
$V_E = C_E * C_N$
$V_{EF} = V_E/12$
$CFP = P_E * \left(A_e/A_t\right)_{iter} * g_o * A_t/\left(\omega_v * V_E\right)$
$L_p = \left[1 - 1/2\left(1 + COS\sigma_{eff}\right)\right]/\left[1 + CFP\right]$
$L_\Delta = 2\left(R_E - \delta/2\right) * \delta/\left(R_E - \delta\right)^2$
$F_{max} = P_c * A_t * \left\{\left[(2/(\gamma+1))^{f(\gamma)} * 2\gamma^2\right]/(\gamma-1)\right\}^{1/2}$
$C_F = \left\{\left(2\gamma^2/(\gamma-1)\right) * \left(2/(\gamma+1)\right)^{f(\gamma)}\left[1 - \left(P_E/P_c\right)^{(\gamma-1)/\gamma}\right]\right\}^{1/2} + \left(\left(P_E - P_A\right)/P_c\right) * \left(A_e/A_t\right)_{aero}$
$F_{theor} = C_F * P_c * A_t$
$L_N = F_{max} - F_{theor}\ F_{max}$
$L_T = 1 - \left(1 - L_P\right) * \left(1 - L_\delta\right) * (1 - L_N)$
$FLTOTP = L_T * 100$
$F_{net}\ \ _{max} * \left(1 - L_T\right)$


PRINT RESULTS
151
151 PRINT: F_{net}, D_t, ΔP, FLTOTP, ω_v, C_N
153
OFF
173
SSW2
ON
154
154 PRINT: ω_t, IN2
156 PRINT: $(A_e/A_t)_{aero}$, $(A_e/A_t)_{iter}$, IN3
159 PRINT: P_c, P_E, T_E, C_E, V_{EF}
PRINT: T_R/T_E, μ_o, R_μ, R#
165 PRINT: δ, δ^*, RE_{eff}
168 PRINT: F_{theor}, F_{max}
170 PRINT: L_p, L_S, L_N, L_T

II. Computer List Print for Net Thrust Prediction Program

```
 1 READ 2,MAX1,MAX2,MAX3,EPS1,EPS2,EPS3
 2 FORMAT (6F10.5)
 3 N1=3
 4 DO 173 I=1,N1
 5 READ 6,CDV,TB,TO,DB,DS,ARTGEO,CV,SIGDEG,GAMMA
 6 FORMAT(F10.7,F10.5,F5.1,2F5.3,F10.3,F10.2,F5.2,F10.5)
 7 READ 8,R,PA,PO,PCINIT,DT,CNINIT,PI,GO
 8 FORMAT(8F10.5)
 9 RS=DS/2.
10 RB=DB/2.
11 A1=SQRTF((RB**2)-(RS**2))
12 A2=A1+TB
13 PHI2=ATANF(RS/A2)
14 Q=(RS/SINF(PHI2))-RB
15 B=RB*RS/(RB+Q)
16 E=A2*B/RS
17 H=A2-E
18 AO=PI*(RS+B)*SQRTF((H**2)+((RS-B)**2))
19 AOX=PI*RS*RS
20 IF(AO-AOX)22,21,21
21 AO=AOX
22 PRINT 23,PO
23 FORMAT(1H1,4X16HINLET PRESSURE =,F7.3,1X9H(LBS/IN2))
24 PRINT 25,CDV
25 FORMAT(5X37HVALVE ORIFICE DISCHARGE COEFFICIENT =,F7.4)
26 PRINT 27,TB
27 FORMAT(5X13HBALL TRAVEL =,F7.5,1X4H(IN))
28 PRINT 29,ARTGEO
29 FORMAT(5X29HNOZZLE GEOMETRIC AREA RATIO =,F8.3)
30 PRINT 31,SIGDEG
31 FORMAT(5X19HNOZZLE HALF-ANGLE =,F5.1,1X5H(DEG))
32 PRINT 33,TO
33 FORMAT(5X23HINLET GAS TEMPERATURE =,F6.1,1X7H(DEG C))
34 PRINT 35
35 FORMAT(5X19HNITROGEN PROPELLANT)
36 PRINT 37,AO
37 FORMAT(5X30HVALVE ORIFICE EFFECTIVE AREA =,F7.5,1X5H(IN2))
38 PRINT 39,AOX
39 FORMAT(5X17HVALVE SEAT AREA =,F7.5,1X5H(IN2)//)
40 PRINT 41
41 FORMAT(5X10HNET THRUST,11X6HNOZZLE,7X5HVALVE,9X6HTHRUST,10X6HWEIGH
421T,9X9HEXIT MACH)
43 PRINT 44
44 FORMAT(7X5H(LBS),14X6HTHROAT,6X8HPRESSURE,7X6HLOSSES,9X8HFLOWRATE,
4519X6HNUMBER)
46 PRINT 47
47 FORMAT(25X8HDIAMETER,7X4HDROP,7X10H(PER CENT),7X9H(LBS/SEC))
48 PRINT 49
49 FORMAT(27X4H(IN),6X9H(LBS/IN2) /)
50 RT=DT/2.
51 AT=PI*RT*RT
52 AE=ARTGEO*AT
53 DE=SQRTF(4.*AE/PI)
54 RE=DE/2.
55 SIGMA=(SIGDEG/360.)*2.*PI
56 SL=(RE-RT)*COSF(SIGMA)/SINF(SIGMA)
57 FGAM=(GAMMA+1.)/(GAMMA-1.)
58 PC=PCINIT
59 CPC=((GAMMA-1 )/2.)*((AT/(AO*CDV))**2.)*((2./(GAMMA+1.))**FGAM)
```

```
 60 IN1=1
 61 FPC=((PC/PO)**((2.-(2.*GAMMA))/GAMMA))-((PC/PO)**((1.-GAMMA)/GAMMA
 621))-CPC
 63 DFPC=(((2.-(2.*GAMMA))/GAMMA)*(PO**(((2.*GAMMA)-2.)/GAMMA))*(PC**(
 641(2.-(3.*GAMMA))/GAMMA)))-(((1.-GAMMA)/GAMMA)*(PO**((GAMMA-1.)/GAMM
 652A))*(PC**((1.-(2.*GAMMA))/GAMMA)))
 66 PCN=PC-(FPC/DFPC)
 67 IF(SENSE SWITCH 2)68,71
 68 PRINT 69,FPC,DFPC,PCN,IN1
 69 FORMAT(2X5HFPC =,E15.8,5X6HDFPC =,E15.8,5X5HPCN =,E15.8,5X10HITER(
 701PC) =,I4)
 71 IN1=IN1+1
 72 IF(ABSF(PCN-PC)-EPS1)78,78,73
 73 PC=PCN
 74 IF(MAX1-IN1)75,75,61
 75 PRINT 76,PC
 76 FORMAT(2X24H TERATION LIMIT EXCEEDED,5X9HPC(DIV) =,E15.8)
 77 PAUSE
 78 PC=PCN
 79 DELP=PO-PC
 80 TR=(9.*TO)/5.+491.69
 81 WODOT=AO*CDV*PO*((PC/PO)**(1./GAMMA))*SQRTF((2.*GO/(R*TR))*(GAMMA/
 821(GAMMA-1.))*(1.-((PC/PO)**((GAMMA-1.)/GAMMA))))
 83 WTDOT=PC*AT*SQRTF((GAMMA*GO/(R*TR))*((2./(GAMMA+1.))**((GAMMA+1.)/
 841(GAMMA-1.))))
 85 ARTERO=.5*ARTGEO
 86 CN=CNINIT
 87 IN3=1
 88 IN2=0
 89 C1=(GAMMA+1.)/(2.*(GAMMA-1.))
 90 C2=(GAMMA-1.)/2.
 91 C3=((GAMMA+1.)/2.)**C1
 92 FCN=C3*CN*((1.+(C2*CN*CN))**(-C1))-(1./ARTERO)
 93 DFCN=C3*(2.*C2*CN*CN*(-C1)*((1.+(C2*CN*CN))**(-C1-1.))+((1.+(C2*CN
 941*CN))**(-C1)))
 95 CNN=CN-(FCN/DFCN)
 96 IN2=IN2+1
 97 IF(SENSE SWITCH 2)98,100
 98 PRINT 99,FCN,DFCN,CNN
 99 FORMAT(2X5HFCN =,E15.8,5X6HDFCN =,E15.8,5X5HCNN =,E15.8)
100 IF(ABSF(CNN-CN)-EPS2)105,105,101
101 CN=CNN
102 IF(MAX2-IN2)103,103,92
103 PRINT 104,CN
104 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HME(DIV) =,E15.8)
105 CN=CNN
106 TRAT=1.+((GAMMA-1.)*CN*CN/2.)
107 UO=(2.270E-08)*(TR**(3./2.))/(TR+198.6)
108 RENOU=(CN/UO)*SQRTF(GAMMA/((GAMMA-1.)*CV*TR))*(TRAT**((GAMMA-2.)/(
1091GAMMA-1.)))*(((TR/TRAT)+198.6)/(TR+198.6))
110 RENO=12.*RENOU*SL*PC
111 DELTA=.645*SL/SQRTF(RENO)
112 IF(CN-6.5)113,113,116
113 DELSTR=DELTA*(-.00022*CN**6+.00671*CN**5-.07610*CN**4+.39770*CN**3
1141-.30876*CN**2+.99230*CN+2.28324)
115 GO TO 123
116 IF(CN-7.5)117,117,119
117 DELSTR=DELTA*(8.6*CN-25.9)
118 GO TO 123
```

```
119 IF(CN-9.0)120,120,122
120 DELSTR=DELTA*(10.0*CN-36.4)
121 GO TO 123
122 DELSTR=DELTA*(10.9*CN-44.4)
123 REEFF=RE-DELSTR
124 IF(REEFF)129,129,125
125 ARITER=(REEFF*REEFF)/(RT*RT)
126 IF(ABSF(ARTERO-ARITER)-EPS3)133,133,127
127 IF(MAX3-IN3)131,131,128
128 IN3=IN3+1
129 ARTERO=(ARTERO+ARITER)/2.
130 GO TO 88
131 PRINT 132,ARIT
132 FORMAT(2X24H    TION LIMIT EXCEEDED,5X13HARTERO(DIV) =,E15.8)
133 SIGEFF=ATANF(.c_FF/SL)
134 PE=PO*((1.+(((GAMMA-1.)/2.)*CN*CN))**(-GAMMA/(GAMMA-1.)))
135 TE=TR/TRAT
136 CE=SQRTF(GO*GAMMA*R*TE)
137 VE=CE*CN
138 VEF=VE/12.
139 CFP=PE*ARITER*GO*AT/(WODOT*VE)
140 FP=(1.-.5*(1.+COSF(SIGEFF)))/(1.+CFP)
141 FDEL=2.*(RE-(DELTA/2.))*DELTA/((RE-DELSTR)*(RE-DELSTR))
142 FMAX=PC*AT*SQRTF(2.*GAMMA*GAMMA*((2./(GAMMA+1.))**FGAM)/(GAMMA-1.)
1431)
144 CF=SQRTF(((2.*GAMMA*GAMMA)/(GAMMA-1.))*((2./(GAMMA+1.))**FGAM)*(1.
1451-((PE/PC)**((GAMMA-1.)/GAMMA))))+((PE-PA)*ARITER/PC)
146 FTHEOR=CF*PC*AT
147 FN=(FMAX-FTHEOR)/FMAX
148 FLTOT=1.-((1.-FP)*(1.-FDEL)*(1.-FN))
149 FLTOTP=FLTOT*100.
150 FNET=FMAX*(1.-FLTOT)
151 PRINT 152,FNET,DT,DELP,FLTOTP,WODOT,CN
152 FORMAT(2X,E15.8,7X,F8.5,5X,F7.4,8X,F6.2,6X,E15.8,6X,F6.3)
153 IF(SENSE SWITCH 2)154,173
154 PRINT 155,WTDOT,IN2
155 FORMAT(2X7HWTDOT =,E15.8,5X10HITER(ME) =,I4)
156 PRINT 157,ARTERO,ARITER,IN3
157 FORMAT(2X13HAE/AT(INIT) =,E15.8,5X13HAE/AT(ITER) =,E15.8,5X10HITER
1581(BL) =,I4)
159 PRINT 160,PC,PE,TE,CE,VEF
160 FORMAT(2X4HPC =,E15.8,5X4HPE =,E15.8,5X4HTE =,E15.8,5X4HCE =,E15.8
1611,5X5HVEF =,E15.8)
162 PRINT 163,TRAT,UO,RENOU,RENO
163 FORMAT(2X6HTRAT =,E15.8,5X7HMU(O) =,E15.8,5X10HRENO(MU) =,E15.8,5X
16416HRENO =,E15.8)
165 PRINT 166,DELTA,DELSTR,REEFF
166 FORMAT(2X7HDELTA =,E15.8,5X13HDELTA(STAR) =,E15.8,5X9HRE(EFF) =,E1
16715.8)
168 PRINT 169,FTHEOR,FMAX
169 FORMAT(2X8HFTHEOR =,E15.8,5X6HFMAX =,E15.8)
170 PRINT 171,FP,FDEL,FN,FLTOT
171 FORMAT(2X4HFP =,E15.8,5X6HFDEL =,E15.8,5X4HFN =,E15.8,5X7HFLTOT =,
1721E15.8)
173 CONTINUE
174 END
```

III. Output Data from Net Thrust Prediction Program

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .3478
BALL TRAVEL = .00850 (IN)
NOZZLE GEOMETRIC AREA RATIO = 260.511
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00250 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.23268041E-02	.01130	.0465	14.29	.33859588E-04	6.600

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .3478
BALL TRAVEL = .00850 (IN)
NOZZLE GEOMETRIC AREA RATIO = 260.511
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00250 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.39887409E-02	.0147[illegible]	.1325	12.68	.56971131E-04	6.750

Appendix D

List of Prints of Parametric Plot Series

This appendix contains the Fortran list prints programmed for the IBM 1620 computer and the IBM 1627 plotter for the following figures:

Figures	Title
5	Valve pressure ratio
6	Flow rate versus chamber pressure ratio
7	Flow rate ratio versus temperature
8	Net thrust versus pressure ratio
9	Net thrust versus inlet pressure
10	Net thrust versus nozzle area ratio

The list prints are in the order given above. Also, output data used in plotting each curve are summarized at the end of each list print.

I. List Print for Fig. 5

```
      GAMMA=1.401
      PI=3.1416
      READ 1,AOCRMN,AOCRMX,AOCRLN,AOCRIC,PRATMN,PRATMX,PRATLN,PRATIC
    1 FORMAT(2F10.7,F5.1,F10.7,2F5.3,F5.1,F5.3)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.1)
      XMIN=AOCRMN
      XMAX=AOCRMX
      XLEN=AOCRLN
      XINC=AOCRIC
      YMIN=PRATMN
      YMAX=PRATMX
      YLEN=PRATLN
      YINC=PRATIC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 4 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    3 FORMAT(F6.3)
    4 DL=DL+1.
      DL=0.
      DO 6 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    5 FORMAT(F6.3)
    6 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(0,0.1,0)
    7 FORMAT(19HNITROGEN PROPELLANT)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(0,0.1,0)
    8 FORMAT(6HAO  CR)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
      CALL CHAR(0,0.2,0)
    9 FORMAT(20HVALVE PRESSURE RATIO)
      CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
     1C))/2.))
      CALL CHAR(0,0.1,1)
   10 FORMAT(5HPC/P0)
      FGAM=(GAMMA+1.)/(GAMMA-1.)
      N1=10
      N2=50
      FLON2=N2
      DO 35 I=1,N1
      READ 11,DT
```

```
11 FORMAT(F10.5)
   AT=PI*((DT/2.)**2.)
   PRINT 12,DT
12 FORMAT(1H1,4X29HNOZZLE THROAT DIAMETER(IN.) =,F7.4)
   PRINT 13,AT
13 FORMAT(5X25HNOZZLE THROAT AREA(IN2) =,F9.7)
   PRINT 14
14 FORMAT(5X19HNITROGEN PROPELLANT)
   PRINT 15
15 FORMAT(//)
   PRINT 16
16 FORMAT(2X24HVALVE CHAMBER PRESSURE  ,5X15HEFFECTIVE VALVE)
   PRINT 17
17 FORMAT(3X20HVALVE INLET PRESSURE,9X12HORIFICE AREA)
   PRINT 18
18 FORMAT(10X7H(PC/PO),16X10H(AOCR-IN2),/)
   AOCR=.0001
   PRATIT=.95
   DO 34 J=1,N2
   MAX1=20
   IN=0
   EPS1=.001
   PRAT=PRATIT
   CPC=((GAMMA-1.)/2.)*((AT/AOCR)**2)*((2./(GAMMA+1.))**FGAM)
19 FPRAT=(PRAT**((2.-(2.*GAMMA))/GAMMA))-(PRAT**((1.-GAMMA)/GAMMA))-C
  1PC
   IN=IN+1
   DFPRAT=(((2.-(2.*GAMMA))/GAMMA)*(PRAT**((2.-(3.*GAMMA))/GAMMA)))-(
  1((1.-GAMMA)/GAMMA)*(PRAT**((1.-(2.*GAMMA))/GAMMA)))
   PRATN=PRAT-(FPRAT/DFPRAT)
   IF(SENSE SWITCH 2)20,22
20 PRINT 21,FPRAT,DFPRAT,PRATN,IN,CPC
21 FORMAT(2X7HFPRAT =,E15.8,5X8HDFPRAT =,E15.8,5X7HPRATN =,E15.8,5X4H
  1IN =,I4,5X5HCPC =,E15.8)
22 IF(ABSF(PRATN-PRAT)-EPS1)26,26,23
23 PRAT=PRATN
   IF(MAX1-IN)24,24,19
24 PRINT 25,PRAT
25 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X11HPRAT(DIV) =,E15.8)
   PAUSE
26 PRAT=PRATN
   PRINT 27,PRAT,AOCR
27 FORMAT(9X,F8.5,17X,F7.4)
   IF(PRAT-PRATMN)33,33,28
28 IF(PRATMX-PRAT)33,33,29
29 IF(I-1)32,30,32
30 IF(J-2)32,31,32
31 PAUSE
32 CALL PLOT(90,AOCR,PRAT)
33 AOCR=AOCR+((AOCRMX-AOCRMN)/FLON2)
34 CONTINUE
   CALL PLOT(99)
35 CONTINUE
   END
```

II. Output Data for Fig. 5

NOZZLE THROAT DIAMETER(IN.) = .0050
NOZZLE THROAT AREA(IN2) = .0000196
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.99103	.0001
.99774	.0002
.99899	.0003
.99943	.0004
.99963	.0005
.99974	.0006
.99981	.0007
.99985	.0008
.99988	.0009
.99990	.0010
.99992	.0011
.99993	.0012
.99994	.0013
.99995	.0014
.99995	.0015
.99996	.0016
.99996	.0017
.99997	.0018
.99997	.0019
.99997	.0020
.99997	.0021
.99998	.0022
.99998	.0023
.99998	.0024
.99998	.0025
.99998	.0026
.99998	.0027
.99998	.0028
.99998	.0029
.99999	.0030
.99999	.0031
.99999	.0032
.99999	.0033
.99999	.0034
.99999	.0035
.99999	.0036
.99999	.0037
.99999	.0038
.99999	.0039
.99999	.0040
.99999	.0041
.99999	.0042
.99999	.0043
.99999	.0044
.99999	.0045
.99999	.0046
.99999	.0047
.99999	.0048
.99999	.0049
.99999	.0050

NOZZLE THROAT DIAMETER(IN.) = .0100
NOZZLE THROAT AREA(IN2) = .0000785
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.87245	.0001
.96500	.0002
.98416	.0003
.99103	.0004
.99424	.0005
.99599	.0006
.99705	.0007
.99774	.0008
.99821	.0009
.99855	.0010
.99880	.0011
.99899	.0012
.99914	.0013
.99926	.0014
.99935	.0015
.99943	.0016
.99949	.0017
.99955	.0018
.99959	.0019
.99963	.0020
.99967	.0021
.99970	.0022
.99972	.0023
.99974	.0024
.99976	.0025
.99978	.0026
.99980	.0027
.99981	.0028
.99982	.0029
.99983	.0030
.99984	.0031
.99985	.0032
.99986	.0033
.99987	.0034
.99988	.0035
.99988	.0036
.99989	.0037
.99989	.0038
.99990	.0039
.99990	.0040
.99991	.0041
.99991	.0042
.99992	.0043
.99992	.0044
.99992	.0045
.99993	.0046
.99993	.0047
.99993	.0048
.99993	.0049
.99994	.0050

NOZZLE THROAT DIAMETER(IN.) = .0150
NOZZLE THROAT AREA(IN2) = .0001767
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.56425	.0001
.84350	.0002
.92433	.0003
.95609	.0004
.97147	.0005
.98003	.0006
.98525	.0007
.98867	.0008
.99103	.0009
.99272	.0010
.99398	.0011
.99493	.0012
.99568	.0013
.99627	.0014
.99675	.0015
.99714	.0016
.99747	.0017
.99774	.0018
.99797	.0019
.99817	.0020
.99834	.0021
.998[illegible]8	.0022
.998[illegible]1	.0023
.99872	.0024
.99882	.0025
.99891	.0026
.99899	.0027
.99906	.0028
.99912	.0029
.99918	.0030
.99923	.0031
.99928	.0032
.99932	.0033
.99936	.0034
.99940	.0035
.99943	.0036
.99946	.0037
.99949	.0038
.99951	.0039
.99954	.0040
.99956	.0041
.99958	.0042
.99960	.0043
.99962	.0044
.99963	.0045
.99965	.0046
.99966	.0047
.99968	.0048
.99969	.0049
.99970	.0050

NOZZLE THROAT DIAMETER(IN.) = .0200
NOZZLE THROAT AREA(IN2) = .0003141
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.62364	.0001
.79238	.0002
.87245	.0003
.91473	.0004
.93932	.0005
.95474	.0006
.96500	.0007
.97216	.0008
.97733	.0009
.98120	.0010
.98416	.0011
.98647	.0012
.98831	.0013
.98980	.0014
.99103	.0015
.99204	.0016
.99290	.0017
.99362	.0018
.99424	.0019
.99477	.0020
.99523	.0021
.99564	.0022
.99599	.0023
.99630	.0024
.99658	.0025
.99683	.0026
.99705	.0027
.99725	.0028
.99743	.0029
.99759	.0030
.99774	.0031
.99787	.0032
.99800	.0033
.99811	.0034
.99821	.0035
.99831	.0036
.99839	.0037
.99848	.0038
.99855	.0039
.99862	.0040
.99868	.0041
.99874	.0042
.99880	.0043
.99885	.0044
.99890	.0045
.99895	.0046
.99899	.0047
.99903	.0048
.99907	.0049
	.0050

..'LE THROAT DIAMETER(IN.) = .0250
.. 'LE THROAT AREA(IN2) = .0004908
. OGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (ACOR-IN2)
.39038	.0002
.60345	.0003
.73402	.0004
.81316	.0005
.86298	.0006
.89582	.0007
.91838	.0008
.93447	.0009
.9463[illegible]	.0010
.95523	.0011
.96213	.0012
.96756	.0013
.97191	.0014
.97545	.0015
.97836	.0016
.98079	.0017
.98283	.0018
.98456	.0019
.98605	.0020
.98733	.0021
.9884[illegible]	.0022
.98942	.0023
.9[illegible]37	.0024
.[illegible]	.0025
.99170	.0026
.99230	.0027
.99283	.0028
.99332	.0029
.99375	.0030
.99415	.0031
.99450	.0032
.99483	.0033
.99513	.0034
.99540	.0035
.99565	.0036
.99588	.0037
.99610	.0038
.99629	.0039
.99647	.0040
.99664	.0041
.99680	.0042
.99695	.0043
.99708	.0044
.99721	.0045
.99733	.0046
.99744	.0047
.99755	.0048
.99765	.0049
.99774	.0050

NOZZLE THROAT DIAMETER(IN.) = .0300
NOZZLE THROAT AREA(IN2) = .0007068
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.41178	.0003
.56425	.0004
.67343	.0005
.75003	.0006
.80430	.0007
.84350	.0008
.87245	.0009
.89431	.0010
.91114	.0011
.92433	.0012
.93485	.0013
.94335	.0014
.95031	.0015
.95609	.0016
.96092	.0017
.96500	.0018
.96848	.0019
.97147	.0020
.97406	.0021
.97631	.0022
.97829	.0023
.98003	.0024
.98156	.0025
.98293	.0026
.98416	.0027
.98525	.0028
.98624	.0029
.98713	.0030
.98794	.0031
.98867	.0032
.98934	.0033
.98995	.0034
.99051	.0035
.99103	.0036
.99150	.0037
.99194	.0038
.99234	.0039
.99272	.0040
.99307	.0041
.99339	.0042
.99369	.0043
.99398	.0044
.99424	.0045
.99448	.0046
.99472	.0047
.99493	.0048
.99514	.0049
.99533	.0050

NOZZLE THROAT DIAMETER(IN.) = .0350
NOZZLE THROAT AREA(IN2) = .0009621
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.51960	.0005
.61350	.0006
.68610	.0007
.74203	.0008
.78538	.0009
.81932	.0010
.84620	.0011
.86774	.0012
.88522	.0013
.89956	.0014
.91144	.0015
.92138	.0016
.92977	.0017
.93691	.0018
.94304	.0019
.94832	.0020
.95292	.0021
.95693	.0022
.96046	.0023
.96358	.0024
.96634	.0025
.96881	.0026
.97101	.0027
.97300	.0028
.97478	.0029
.97640	.0030
.97787	.0031
.97920	.0032
.98042	.0033
.98154	.0034
.98256	.0035
.98350	.0036
.98437	.0037
.98517	.0038
.98591	.0039
.98659	.0040
.98723	.0041
.98783	.0042
.98838	.0043
.98890	.0044
.98938	.0045
.98983	.0046
.99026	.0047
.99065	.0048
.99103	.0049
.99138	.0050

NOZZLE THROAT DIAMETER(IN.) = .0400
NOZZLE THROAT AREA(IN2) = .0012566
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.37808	.0005
.47445	.0006
.55608	.0007
.62364	.0008
.67905	.0009
.72441	.0010
.76165	.0011
.79238	.0012
.81790	.0013
.83924	.0014
.85721	.0015
.87245	.0016
.88547	.0017
.89665	.0018
.90632	.0019
.91473	.0020
.92209	.0021
.92855	.0022
.93426	.0023
.93932	.0024
.94383	.0025
.94786	.0026
.95148	.0027
.95474	.0028
.95769	.0029
.96036	.0030
.96279	.0031
.96500	.0032
.96703	.0033
.96888	.0034
.97059	.0035
.97216	.0036
.97360	.0037
.97494	.0038
.97618	.0039
.97733	.0040
.97840	.0041
.97940	.0042
.98033	.0043
.98120	.0044
.98201	.0045
.98277	.0046
.98349	.0047
.98416	.0048
.98479	.0049
.98538	.0050

NOZZLE THROAT DIAMETER(IN.) = .0450
NOZZLE THROAT AREA(IN2) = .0015904
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.43103	.0007
.50227	.0008
.56425	.0009
.61755	.0010
.66312	.0011
.70202	.0012
.73526	.0013
.76372	.0014
.78818	.0015
.80929	.0016
.82758	.0017
.84350	.0018
.85742	.0019
.86963	.0020
.88041	.0021
.88995	.0022
.89843	.0023
.90599	.0024
.91276	.0025
.91885	.0026
.92433	.0027
.92929	.0028
.93379	.0029
.93788	.0030
.94161	.0031
.94502	.0032
.94814	.0033
.95101	.0034
.95365	.0035
.95609	.0036
.95834	.0037
.96042	.0038
.96235	.0039
.96415	.0040
.96582	.0041
.96738	.0042
.96884	.0043
.97020	.0044
.97147	.0045
.97267	.0046
.97379	.0047
.97485	.0048
.97584	.0049
.97678	.0050

NOZZLE THROAT DIAMETER(IN.) = .0500
NOZZLE THROAT AREA(IN2) = .0019635
NITROGEN PROPELLANT

VALVE CHAMBER PRESSURE / VALVE INLET PRESSURE (PC/PO)	EFFECTIVE VALVE ORIFICE AREA (AOCR-IN2)
.45264	.0009
.50888	.0010
.55904	.0011
.60345	.0012
.64259	.0013
.67704	.0014
.70734	.0015
.73402	.0016
.75755	.0017
.77835	.0018
.79678	.0019
.81316	.0020
.82775	.0021
.84079	.0022
.85248	.0023
.86298	.0024
.87245	.0025
.88101	.0026
.88877	.0027
.89582	.0028
.90224	.0029
.90810	.0030
.91346	.0031
.91838	.0032
.92291	.0033
.92707	.0034
.93092	.0035
.93447	.0036
.93776	.0037
.94082	.0038
.94366	.0039
.94630	.0040
.94876	.0041
.95106	.0042
.95322	.0043
.95523	.0044
.95712	.0045
.95889	.0046
.96056	.0047
.96213	.0048
.96361	.0049
.96500	.0050

III. List Print for Fig. 6

```
      R=55.16*12.
      GO=386.0677
      TO=25.
      TR=(9.*TO/5.)+491.69
      GAMMA=1.401
      PI=3.1416
      AOCRMN=.0005
      AOCRMX=.0050
      DIMENSION DT(19),WOPO(19,10),PRAT(19,10),WOPOA(19,10)
      READ 1,(DT(L),L=1,19)
    1 FORMAT(5F10.7)
      READ 2,PRATMN,PRATMX,PRATLN,PRATIC,WOPOMN,WOPOMX,WOPOLN,WOPOIC
    2 FORMAT(8F10.5)
      READ 3,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    3 FORMAT(6F5.1,2F10.1)
      XMIN=PRATMN
      XMAX=PRATMX
      XLEN=PRATLN
      XINC=PRATIC
      YMIN=WOPOMN
      YMAX=WOPOMX
      YLEN=WOPOLN
      YINC=WOPOIC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 5 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    4 FORMAT(F5.2)
    5 DL=DL+1.
      DL=0.
      DO 7 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    6 FORMAT(F4.0)
    7 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,TO)
    8 FORMAT(23HGAS INLET TEMPERATURE =,F5.1,1X1HC)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(0,0.1,0)
    9 FORMAT(19HNITROGEN PROPELLANT)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(2,0.1,0)
   10 FORMAT(5HPC/PO)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
```

```
   CALL CHAR(0,0.2,0)
11 FORMAT(28HFLOWRATE VS CHAMBER PRESSURE)
   CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
  1C))/2.))
   CALL CHAR(0,0.1,1)
12 FORMAT(15HW(25 C)/PO X 10)
   FGAM=(GAMMA+1.)/(GAMMA-1.)
   N1=19
   N2=10
   N3=N2-1
   FLON3=N3
   L=1
   DO 31 I=1,N1
   AT=PI*((DT(L)/2.)**2)
   PRINT 13
13 FORMAT(////)
   PRINT 14,DT(L)
14 FORMAT(1H1,4X29HNOZZLE THROAT DIAMETER(IN.) =,F7.4)
   PRINT 15,AT
15 FORMAT(5X25HNOZZLE THROAT AREA(IN2) =,F9.7)
   PRINT 16
16 FORMAT(5X19HNITROGEN PROPELLANT)
   PRINT 17
17 FORMAT(//)
   PRINT 18
18 FORMAT(10X8HWODOT/PO,12X8HWTDOT/PO,13X5HPC/PO,15X5HAO*CR)
   PRINT 19
19 FORMAT(10X9H(IN2/SEC),11X9H(IN2/SEC),32X5H(IN2),/)
   AOCR=AOCRMN
   PRATIT=.95
   DO 29 J=1,N2
   MAX1=20
   IN=0
   PRAT(I,J)=PRATIT
   EPS1=.001
   CPC=((GAMMA-1.)/2.)*((AT/AOCR)**2)*((2./(GAMMA+1.))**FGAM)
20 FPRAT=(PRAT(I,J)**((2.-(2.*GAMMA))/GAMMA))-(PRAT(I,J)**((1.-GAMMA)
  1/GAMMA))-CPC
   DFPRAT=(((2.-(2.*GAMMA))/GAMMA)*(PRAT(I,J)**((2.-(3.*GAMMA))/GAMMA
  1)))-(((1.-GAMMA)/GAMMA)*(PRAT(I,J)**((1.-(2.*GAMMA))/GAMMA)))
   IN=IN+1
   PRATN=PRAT(I,J)-(FPRAT/DFPRAT)
   IF(SENSE SWITCH 2)21,23
21 PRINT 22,FPRAT,DFPRAT,PRATN,CPC,IN
22 FORMAT(2X7HFPRAT =,E15.8,5X8HDFPRAT =,E15.8,5X7HPRATN =,E15.8,5X5H
  1CPC =,E15.8,5X4HIN =,I5)
23 IF(ABSF(PRATN-PRAT(I,J))-EPS1)27,27,24
24 PRAT(I,J)=PRATN
   IF(MAX1-IN)25,25,20
25 PRINT 26,PRAT(I,J)
26 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X11HPRAT(DIV) =,E15.8)
   PAUSE
27 PRAT(I,J)=PRATN
   WOPO(I,J)=AOCR*(PRAT(I,J)**(1./GAMMA))*SQRTF((2.*GO/(R*TR))*(GAMMA
  1/(GAMMA-1.))*(1.-(PRAT(I,J)**((GAMMA-1.)/GAMMA))))*(.1E7)
   WTPO=PRAT(I,J)*AT*SQRTF((GAMMA*GO/(R*TR))*((2./(GAMMA+1.))**FGAM))
  1*(.1E7)
   WOPOA(I,J)=WOPO(I,J)/(.1E7)
   WTPOA=WTPO/(.1E7)
```

```
      PRINT 28,WOPOA(I,J),WTPOA,PRAT(I,J),AOCR
   28 FORMAT(5X,E15.8,5X,E15.8,5X,E15.8,5X,E15.8)
      AOCR=AOCR+((AOCRMX-AOCRMN)/FLON3)
   29 CONTINUE
      IF(L-N1)30,31,31
   30 L=L+1
   31 CONTINUE
      DO 40 J=1,N2
      DO 39 I=1,N1
      IF(PRAT(I,J)-PRATMN)39,32,32
   32 IF(PRATMX-PRAT(I,J))39,33,33
   33 IF(WOPO(I,J)-WOPOMN)39,34,34
   34 IF(WOPOMX-WOPO(I,J))39,35,35
   35 IF(I-2)38,36,38
   36 IF(J-1)38,37,38
   37 PAUSE
   38 CALL PLOT(90,PRAT(I,J),WOPO(I,J))
   39 CONTINUE
      CALL PLOT(99)
   40 CONTINUE
      END
```

IV. Output Data for Fig. 6

NOZZLE THROAT DIAMETER(IN.) = .0050
NOZZLE THROAT AREA(IN2) = .0000196
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.44315664E-06	.44316816E-06	.99963874E+00	.50000000E-03
.44345646E-06	.44328830E-06	.99990972E+00	.10000000E-02
.44325827E-06	.44331056E-06	.99995996E+00	.15000000E-02
.44773804E-06	.44331826E-06	.99997729E+00	.20000000E-02
.44646691E-06	.44332194E-06	.99998562E+00	.25000000E-02
.44519088E-06	.44332393E-06	.99999011E+00	.30000000E-02
.45238289E-06	.44332506E-06	.99999264E+00	.35000000E-02
.45447678E-06	.44332574E-06	.99999418E+00	.40000000E-02
.44710744E-06	.44332635E-06	.99999554E+00	.45000000E-02
.45697694E-06	.44332666E-06	.99999626E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0075
NOZZLE THROAT AREA(IN2) = .0000441
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.99570737E-06	.99566527E-06	.99817193E+00	.50000000E-03
.99744402E-06	.99703219E-06	.99954231E+00	.10000000E-02
.99791032E-06	.99728566E-06	.99979540E+00	.15000000E-02
.99806886E-06	.99737455E-06	.99988552E+00	.20000000E-02
.99828853E-06	.99741582E-06	.99992691E+00	.25000000E-02
.99887463E-06	.99743800E-06	.99994913E+00	.30000000E-02
.10022992E-05	.99745143E-06	.99996259E+00	.35000000E-02
.10041977E-05	.99746012E-06	.99997132E+00	.40000000E-02
.10074106E-05	.99746608E-06	.99997729E+00	.45000000E-02
.10030702E-05	.99747055E-06	.99998176E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0100
NOZZLE THROAT AREA(IN2) = .0000785
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.17631781E-05	.17631054E-05	.99424363E+00	.50000000E-03
.17708268E-05	.17707509E-05	.99855503E+00	.10000000E-02
.17722703E-05	.17721737E-05	.99935738E+00	.15000000E-02
.17726265E-05	.17726727E-05	.99963874E+00	.20000000E-02
.17735935E-05	.17729028E-05	.99976854E+00	.25000000E-02
.17728805E-05	.17730284E-05	.99983937E+00	.30000000E-02
.17756622E-05	.17731037E-05	.99988184E+00	.35000000E-02
.17738258E-05	.17731532E-05	.99990972E+00	.40000000E-02
.17754008E-05	.17731868E-05	.99992865E+00	.45000000E-02
.17804892E-05	.17732104E-05	.99994200E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0125
NOZZLE THROAT AREA(IN2) = .0001227
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.27321832E-05	.27321606E-05	.98605411E+00	.50000000E-03
.27609589E-05	.27610477E-05	.99347960E+00	.10000000E-02
.27666688E-05	.27664584E-05	.99843240E+00	.15000000E-02
.27687774E-05	.27683573E-05	.99911768E+00	.20000000E-02
.27700214E-05	.27692365E-05	.99943499E+00	.25000000E-02
.27696100E-05	.27697151E-05	.99960780E+00	.30000000E-02
.27713906E-05	.27700028E-05	.99971160E+00	.35000000E-02
.27728251E-05	.27701902E-05	.99977918E+00	.40000000E-02
.27697326E-05	.27703191E-05	.99982573E+00	.45000000E-02
.27725718E-05	.27704103E-05	.99985868E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0150
NOZZLE THROAT AREA(IN2) = .0001767
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.38761998E-05	.38761552E-05	.97147844E+00	.50000000E-03
.39609534E-05	.39609283E-05	.99272507E+00	.10000000E-02
.39769867E-05	.39770058E-05	.99675457E+00	.15000000E-02
.39828294E-05	.39826610E-05	.99817193E+00	.20000000E-02
.39852725E-05	.39852844E-05	.99882946E+00	.25000000E-02
.39873358E-05	.39867093E-05	.99918657E+00	.30000000E-02
.39878316E-05	.39875707E-05	.99940246E+00	.35000000E-02
.39897760E-05	.39881286E-05	.99954231E+00	.40000000E-02
.39884098E-05	.39885133E-05	.99963874E+00	.45000000E-02
.39901507E-05	.39887865E-05	.99970719E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0175
NOZZLE THROAT AREA(IN2) = .0002405
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.51501630E-05	.51501555E-05	.94832846E+00	.50000000E-03
.53580024E-05	.53579178E-05	.98659965E+00	.10000000E-02
.53984651E-05	.53982008E-05	.99400248E+00	.15000000E-02
.54124438E-05	.54124083E-05	.99661858E+00	.20000000E-02
.54199[illegible]-05	.54190056E-05	.99783336E+00	.25000000E-02
.54227[illegible]-05	.54225951E-05	.99849432E+00	.30000000E-02
.54251910E-05	.54247626E-05	.99889347E+00	.35000000E-02
.54258992E-05	.54261710E-05	.99915280E+00	.40000000E-02
.54268155E-05	.54271365E-05	.99933058E+00	.45000000E-02
.54277094E-05	.54278260E-05	.99945755E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0[illegible]
NOZZLE THROAT AREA(IN2) = .0003141
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.64884840E-05	.64884758E-05	.91473908E+00	.50000000E-03
.69326443E-05	.69325063E-05	.97733807E+00	.10000000E-02
.70210325E-05	.70209675E-05	.98980923E+00	.15000000E-02
.70527124E-05	.70524218E-05	.99424363E+00	.20000000E- 2
.70674959E-05	.70670704E-05	.99630876E+00	.25000000E- 2
.70750120E-05	.70750537E-05	.99743426E+00	.30000000E-02
.70799362E-05	.70798738E-05	.99811379E+00	.35000000E-02
.70833073E-05	.70830036E-05	.99855503E+00	.40000000E-02
.70842677E-05	.70851553E-05	.99885837E+00	.45000000E-02
.70868484E-05	.70866909E-05	.99903486E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0225
NOZZLE THROAT AREA(IN2) = .0003976
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.78071074E-05	.78070993E-05	.86963937E+00	.50000000E-03
.86556294E-05	.86556054E-05	.96415513E+00	.10000000E-02
.88316297E-05	.88316859E-05	.98376892E+00	.15000000E-02
.88949040E-05	.88948896E-05	.99080925E+00	.20000000E-02
.89245462E-05	.89244288E-05	.99409964E+00	.25000000E-02
.89406970E-05	.89405521E-05	.99589563E+00	.30000000E-02
.89504125E-05	.89503030E-05	.99698180E+00	.35000000E-02
.89577108E-05	.89566363E-05	.99768725E+00	.40000000E-02
.89613661E-05	.89609874E-05	.99817193E+00	.45000000E-02
.89655314E-05	.89640991E-05	.99851855E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0250
NOZZLE THROAT AREA(IN2) = .0004908
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.90124682E-05	.90124575E-05	.81316324E+00	.50000000E-03
.10488089E-04	.10488084E-04	.94630401E+00	.10000000E-02
.10811237E-04	.10811167E-04	.97545465E+00	.15000000E-02
.10928732E-04	.10928643E-04	.98605411E+00	.20000000E-02
.10983911E-04	.10983823E-04	.99103285E+00	.25000000E-02
.11013991E-04	.11014018E-04	.99375721E+00	.30000000E-02
.11032633E-04	.11032293E-04	.99540616E+00	.35000000E-02
.11043835E-04	.11044191E-04	.99647960E+00	.40000000E-02
.11052743E-04	.11052356E-04	.99721634E+00	.45000000E-02
.11058150E-04	.11058206E-04	.99774420E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0275
NOZZLE THROAT AREA(IN2) = .0005939
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.10015621E-04	.10015617E-04	.74683881E+00	.50000000E-03
.12380289E-04	.12380226E-04	.92316161E+00	.10000000E-02
.12933849E-04	.12933797E-04	.96443994E+00	.15000000E-02
.13138772E-04	.13138491E-04	.97970343E+00	.20000000E-02
.13235312E-04	.13235296E-04	.98692198E+00	.25000000E-02
.13288617E-04	.13288431E-04	.99088411E+00	.30000000E-02
.13321017E-04	.13320660E-04	.99328730E+00	.35000000E-02
.13341458E-04	.13341662E-04	.99485340E+00	.40000000E-02
.13355969E-04	.13356093E-04	.99592951E+00	.45000000E-02
.13366825E-04	.13366431E-04	.99670039E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0300
NOZZLE THROAT AREA(IN2) = .0007068
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.10747871E-04	.10747866E-04	.67343281E+00	.50000000E-03
.14273084E-04	.14273096E-04	.89431435E+00	.10000000E-02
.15166990E-04	.15166926E-04	.95031939E+00	.15000000E-02
.15504799E-04	.15504621E-04	.97147844E+00	.20000000E-02
.15666144E-04	.15665674E-04	.98156965E+00	.25000000E-02
.15754614E-04	.15754487E-04	.98713439E+00	.30000000E-02
.15808530E-04	.15808487E-04	.99051788E+00	.35000000E-02
.15843813E-04	.15843713E-04	.99272507E+00	.40000000E-02
.15868603E-04	.15867949E-04	.99424363E+00	.45000000E-02
.15885810E-04	.15885328E-04	.99533257E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0325
NOZZLE THROAT AREA(IN2) = .0008295
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.11172300E-04	.11172301E-04	.59647253E+00	.50000000E-03
.16101428E-04	.16101408E-04	.85963022E+00	.10000000E-02
.17470888E-04	.17470855E-04	.93274293E+00	.15000000E-02
.18002198E-04	.18002090E-04	.96110480E+00	.20000000E-02
.18258506E-04	.18258209E-04	.97477961E+00	.25000000E-02
.18400825E-04	.18400181E-04	.98235827E+00	.30000000E-02
.18486843E-04	.18486802E-04	.98698282E+00	.35000000E-02
.18543508E-04	.18543418E-04	.99000549E+00	.40000000E-02
.18582612E-04	.18582418E-04	.99208762E+00	.45000000E-02
.18610312E-04	.18610410E-04	.99358207E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0350
NOZZLE THROAT AREA(IN2) = .0009621
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.11287445E-04	.11287445E-04	.51960594E+00	.50000000E-03
.17798198E-04	.17798178E-04	.81932080E+00	.10000000E-02
.19799399E-04	.19799393E-04	.91144469E+00	.15000000E-02
.20600651E-04	.20600622E-04	.94832846E+00	.20000000E-02
.20992097E-04	.20992075E-04	.96634858E+00	.25000000E-02
.21210806E-04	.21210536E-04	.97640519E+00	.30000000E-02
.21344346E-04	.21344326E-04	.98256407E+00	.35000000E-02
.21432009E-04	.21431991E-04	.98659965E+00	.40000000E-02
.21493015E-04	.21492477E-04	.98938407E+00	.45000000E-02
.21536391E-04	.21535945E-04	.99138505E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0375
NOZZLE THROAT AREA(IN2) = .0011044
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.11122550E-04	.11122551E-04	.44602214E+00	.50000000E-03
.19300230E-04	.19300217E-04	.77395234E+00	.10000000E-02
.22101215E-04	.22101179E-04	.88627289E+00	.15000000E-02
.23264699E-04	.23264663E-04	.93292947E+00	.20000000E-02
.23842225E-04	.23842227E-04	.95609017E+00	.25000000E-02
.24167445E-04	.24167203E-04	.96912190E+00	.30000000E-02
.24367534E-04	.24367147E-04	.97713981E+00	.35000000E-02
.24499351E-04	.24498558E-04	.98240953E+00	.40000000E-02
.24589649E-04	.24589446E-04	.98605412E+00	.45000000E-02
.24654956E-04	.24654828E-04	.98867607E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0400
NOZZLE THROAT AREA(IN2) = .0012566
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.10727438E-04	.10727431E-04	.37808574E+00	.50000000E-03
.20553880E-04	.20553871E-04	.72441622E+00	.10000000E-02
.24321822E-04	.24321823E-04	.85721685E+00	.15000000E-02
.25953935E-04	.25953903E-04	.91473908E+00	.20000000E-02
.26779339E-04	.26779357E-04	.94383204E+00	.25000000E-02
.27248411E-04	.27248373E-04	.96036234E+00	.30000000E-02
.27538791E-04	.27538587E-04	.97059090E+00	.35000000E-02
.27730577E-04	.27730026E-04	.97733807E+00	.40000000E-02
.27863718E-04	.27862706E-04	.98201437E+00	.45000000E-02
.27958471E-04	.27958377E-04	.98538627E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0425
NOZZLE THROAT AREA(IN2) = .0014186
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.29586952E+81	.99999999E+93	.99999999E+99	.50000000E-03
.21519809E-04	.21519805E-04	.67185417E+00	.10000000E-02
.26406595E-04	.26406584E-04	.82442079E+00	.15000000E-02
.28624086E-04	.28624083E-04	.89365170E+00	.20000000E-02
.29770062E-04	.29770009E-04	.92942781E+00	.25000000E-02
.30428725E-04	.30428625E-04	.94998996E+00	.30000000E-02
.30839006E-04	.30838917E-04	.96279937E+00	.35000000E-02
.31110842E-04	.31110734E-04	.97128559E+00	.40000000E-02
.31300285E-04	.31299655E-04	.97718380E+00	.45000000E-02
.31437197E-04	.31436101E-04	.98144365E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0450
NOZZLE THROAT AREA(IN2) = .0015904
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.29586952E+81	.99999999E+93	.99999999E+99	.50000000E-03
.22176027E-04	.22176019E-04	.61755136E+00	.10000000E-02
.28303534E-04	.28303528E-04	.78818850E+00	.15000000E-02
.31228429E-04	.31228395E-04	.86963937E+00	.20000000E-02
.32777111E-04	.32777132E-04	.91276810E+00	.25000000E-02
.33679068E-04	.33679052E-04	.93788448E+00	.30000000E-02
.34245433E-04	.34245356E-04	.95365476E+00	.35000000E-02
.34622517E-04	.34622421E-04	.96415518E+00	.40000000E-02
.34885797E-04	.34885397E-04	.97147844E+00	.45000000E-02
.35076171E-04	.35075792E-04	.97678055E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0475
NOZZLE THROAT AREA(IN2) = .0017720
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.29586952E+81	.99999999E+93	.99999999E+99	.50000000E-03
.22518582E-04	.22518576E-04	.56281835E+00	.10000000E-02
.29966664E-04	.29966660E-04	.74897215E+00	.15000000E-02
.33719187E-04	.33719176E-04	.84276069E+00	.20000000E-02
.35760667E-04	.35760645E-04	.89378417E+00	.25000000E-02
.36967583E-04	.36967455E-04	.92394664E+00	.30000000E-02
.37732134E-04	.37732073E-04	.94305710E+00	.35000000E-02
.38244235E-04	.38244150E-04	.95585572E+00	.40000000E-02
.38602906E-04	.38602730E-04	.96481791E+00	.45000000E-02
.38863192E-04	.38863056E-04	.97132433E+00	.50000000E-02

NOZZLE THROAT DIAMETER(IN.) = .0500
NOZZLE THROAT AREA(IN2) = .0019635
NITROGEN PROPELLANT

WODOT/PO (IN2/SEC)	WTDOT/PO (IN2/SEC)	PC/PO	AO*CR (IN2)
.76117548E+66	.41729499E+78	.94127756E+82	.50000000E-03
.22560189E-04	.22560182E-04	.50888204E+00	.10000000E-02
.31358732E-04	.31358723E-04	.70734760E+00	.15000000E-02
.36049872E-04	.36049830E-04	.81316324E+00	.20000000E-02
.38678625E-04	.38678599E-04	.87245946E+00	.25000000E-02
.40258957E-04	.40258850E-04	.90810464E+00	.30000000E-02
.41270495E-04	.41270361E-04	.93092095E+00	.35000000E-02
.41952358E-04	.41952337E-04	.94630401E+00	.40000000E-02
.42432126E-04	.42432044E-04	.95712459E+00	.45000000E-02
.42781635E-04	.42781455E-04	.96500615E+00	.50000000E-02

V. List Print for Fig. 7

```
      READ 1,TOMIN,TOMAX,TOLEN,TOINC,WRATMN,WRATMX,WRATLN,WRATIC
    1 FORMAT(2F10.2,F5.1,F10.2,2F10.7,F5.1,F10.7)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.1)
      TOSTD=25.
      TRSTD=(9.*TOSTD/5.)+491.69
      PRINT 3,TOSTD
    3 FORMAT(2X33HGAS INLET TEMPERATURE REFERENCE =,F5.1,1X5HDEG C,///)
      PRINT 4
    4 FORMAT(2X14HFLOWRATE RATIO,8X24HGAS INLET TEMPERATURE(C) //)
      XMIN=TOMIN
      XMAX=TOMAX
      XLEN=TOLEN
      XINC=TOINC
      YMIN=WRATMN
      YMAX=WRATMX
      YLEN=WRATLN
      YINC=WRATIC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 6 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    5 FORMAT(F5.0)
    6 DL=DL+1.
      DL=0.
      DO 8 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    7 FORMAT(F6.3)
    8 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(0,0.1,0)
    9 FORMAT(19HNITROGEN PROPELLANT)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(0,0.1,0)
   10 FORMAT(7HTO ( C))
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
      CALL CHAR(0,0.2,0)
   11 FORMAT(29H-LOWRATE RATIO VS TEMPERATURE)
      CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YINC
     1))/2.))
      CALL CHAR(0,0.1,1)
   12 FORMAT(9HW/W(25 C))
      TO=TOMIN
      N1=51
```

```
      N2=N1-1
      FLON2=N2
      DO 19 I=1,N1
      TR=(9.*TO/5.)+491.69
      WRAT=SQRTF(TRSTD/TR)
      PRINT 13,WRAT,TO
   13 FORMAT(6X,F7.4,17X,F8.3)
      IF(WRAT-WRATMN)18,18,14
   14 IF(WRATMX-WRAT)18,18,15
   15 IF(I-2)17,16,17
   16 PAUSE
   17 CALL PLOT(90,TO,WRAT)
   18 TO=TO+((TOMAX-TOMIN)/FLON2)
   19 CONTINUE
      END
```

VI. Output Data for Fig. 7

FLOWRATE RATIO	GAS INLET TEMPERATURE(°C)
1.3122	-100.000
1.2936	-95.000
1.2758	-90.000
1.2588	-85.000
1.2424	-80.000
1.2266	-75.000
1.2114	-70.000
1.1968	-65.000
1.1826	-60.000
1.1690	-55.000
1.1558	-50.000
1.1431	-45.000
1.1308	-40.000
1.1188	-35.000
1.1073	-30.000
1.0961	-25.000
1.0852	-20.000
1.0746	-15.000
1.0644	-10.000
1.0544	-5.000
1.0447	0.000
1.0353	5.000
1.0261	10.000
1.0172	15.000
1.0084	20.000
1.0000	25.000
.9917	30.000
.9836	35.000
.9757	40.000
.9680	45.000
.9605	50.000
.9531	55.000
.9460	60.000
.9389	65.000
.9321	70.000
.9254	75.000
.9188	80.000
.9124	85.000
.9060	90.000
.8999	95.000
.8938	100.000
.8879	105.000
.8821	110.000
.8764	115.000
.8708	120.000
.8653	125.000
.8599	130.000
.8546	135.000
.8495	140.000
.8444	145.000
.8394	150.000

VII. List Print for Fig. 8

```
      PO=15.
      PA=0.
      GAMMA=1.401
      PI=3.1416
      R=55.16*12.
      GO=386.0677
      ARTGEO=50.
      SIGDEG=25.
      TO=25.
      TR=(9.*TO/5.)+491.69
      CV=4290.
      DTMIN=.005
      DTMAX=.05
      CNINIT=6.
      DIMENSION XL(6),YL(8)
      READ 1,PRATMN,PRATMX,PRATLN,PRATIC,FNETMN,FNETMX,FNETLN,FNETIC
    1 FORMAT(2F10.7,F5.1,3F10.7,F5.1,F10.7)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.1)
      XMIN=PRATMN
      XMAX=PRATMX
      XLEN=PRATLN
      XINC=PRATIC
      YMIN=FNETMN
      YMAX=FNETMX
      YLEN=FNETLN
      YINC=FNETIC
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 4 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    3 FORMAT(F5.2)
    4 DL=DL+1.
      DL=0.
      DO 6 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    5 FORMAT(F6.3)
    6 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,PO)
    7 FORMAT(4HPO =,F5.1,1X6HLBS/IN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,TO)
    8 FORMAT(4HTO =,F5.1,2X1HC)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.5*YINC)))
      CALL CHAR(0,0.1,0)
    9 FORMAT(19HNITROGEN PROPELLANT)
```

```
      CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,ARTGEO)
   10 FORMAT(12H(AE/AT)GEO =,F5.1)
      CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,SIGDEG)
   11 FORMAT(7HSIGMA =,F5.1)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(0,0.1,0)
   12 FORMAT(5HPC/PO)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
      CALL CHAR(0,0.2,0)
   13 FORMAT(28HNET THRUST VS PRESSURE RATIO)
      CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
     1C))/2.))
      CALL CHAR(0,0.1,1)
   14 FORMAT(9HFNET(LBS))
      N1=6
      N2=46
      N3=N2-1
      FLON3=N3
      MAX1=20
      MAX2=20
      MAX3=20
      EPS1=.001
      EPS2=.001
      EPS3=.001
      PRATIT=.95
      PRAT=PRATIT
      FGAM=(GAMMA+1.)/(GAMMA-1.)
      DO 77 I=1,N1
      READ 15,AOCR
   15 FORMAT(F10.7)
      PRINT 16,PO
   16 FORMAT(1H1,4X22HVALVE INLET PRESSURE =,F7.3,1X7HLBS/IN2)
      PRINT 17,AOCR
   17 FORMAT(5X9HAO X CR =,F7.4,1X3HIN2)
      PRINT 18,ARTGEO
   18 FORMAT(5X19HNOZZLE AREA RATIO =,F8.3)
      PRINT 19,SIGDEG
   19 FORMAT(5X19HNOZZLE HALF-ANGLE =,F5.1,1X3HDEG)
      PRINT 20,TO
   20 FORMAT(5X23HGAS INLET TEMPERATURE =,F5.1,1X5HDEG C)
      PRINT 21
   21 FORMAT(5X19HNITROGEN PROPELLANT)
      PRINT 22
   22 FORMAT(///)
      PRINT 23
   23 FORMAT(5X4HFNET,9X4HPRAT,8X4HDELP,12X5HWDOT,14X2HDT,7X6HFLTOTP,8X
     12HCN)
      PRINT 24
   24 FORMAT(5X4H(LB),20X5H(PSI),10X8H(LB/SEC),12X4H(IN),5X9H(PERCENT),/
     1)
      DT=DTMIN
      DO 76 J=1,N2
      RT=DT/2.
      AT=PI*(RT**2)
      AE=ARTGEO*AT
```

```
   RE=SQRTF(AE/PI)
   DE=RE*2.
   SIGMA=(SIGDEG/360.)*2.*PI
   SL=(RE-RT)*COSF(SIGMA)/SINF(SIGMA)
   CPC=((GAMMA-1.)/2.)*((AT/(AOCR))**2.)*((2./(GAMMA+1.))**FGAM)
   IN1=0
25 FPRAT=(PRAT**((2.-(2.*GAMMA))/GAMMA))-(PRAT**((1.-GAMMA)/GAMMA))-C
  1PC
   DFPRAT=(((2.-(2.*GAMMA))/GAMMA)*(PRAT**((2.-(3.*GAMMA))/GAMMA)))-(
  1((1.-GAMMA)/GAMMA)*(PRAT**((1.-(2.*GAMMA))/GAMMA)))
   IN1=IN1+1
   PRATN=PRAT-(FPRAT/DFPRAT)
   IF(SENSE SWITCH 2)26,28
26 PRINT 27,FPRAT,DFPRAT,PRATN,CPC,IN1
27 FORMAT(2X7HFPRAT =,E15.8,5X8HDFPRAT =,E15.8,5X7HPRATN =,E15.8,5X5H
  1CPC =,E15.8,5X5HIN1 =,I5)
28 IF(ABSF(PRATN-PRAT)-EPS1)32,32,29
29 PRAT=PRATN
   IF(MAX1-IN1)30,30,25
30 PRINT 31,PRAT
31 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X11HPRAT(DIV) =,E15.8)
   PAUSE
32 PRAT=PRATN
   PC=PRAT*PO
   DELP=PO-PC
   WODOT=AOCR*PO*(PRAT**(1./GAMMA))*SQRTF((2.*GO/(R*TR))*(GAMMA/(GAMM
  1A-1.))*(1.-(PRAT**((GAMMA-1.)/GAMMA))))
   WTDOT=PC*AT*SQRTF((GAMMA*GO/(R*TR))*((2./(GAMMA+1.))**((GAMMA+1.)/
  1(GAMMA-1.))))
   ARTERO=.5*ARTGEO
   CN=CNINIT
   IN3=0
33 IN2=0
   IN3=IN3+1
   C1=(GAMMA+1.)/(2.*(GAMMA-1.))
   C2=(GAMMA-1.)/2.
   C3=((GAMMA+1.)/2.)**C1
34 FCN=C3*CN*((1.+(C2*CN*CN))**(-C1))-(1./ARTERO)
   DFCN=C3*(2.*C2*CN*CN*(-C1)*((1.+(C2*CN*CN))**(-C1-1.))+((1.+(C2*CN
  1*CN))**(-C1)))
   CNN=CN-(FCN/DFCN)
   IN2=IN2+1
   IF(SENSE SWITCH 2)35,37
35 PRINT 36,FCN,DFCN,CNN,IN2
36 FORMAT(2X5HFCN =,E15.8,5X6HDFCN =,E15.8,5X5HCNN =,E15.8,5X5HIN2 =,
  1I5)
37 IF(ABSF(CNN-CN)-EPS2)41,41,38
38 CN=CNN
   IF(MAX2-IN2)39,39,34
39 PRINT 40,CN
40 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HME(DIV) =,E15.8)
41 CN=CNN
   TRAT=1.+((GAMMA-1.)*CN*CN/2.)
   UO=(2.270E-08)*(TR**(3/2))/(TR+198.6)
   RENOU=(CN/UO)*SQRTF(GAMMA/((GAMMA-1.)*CV*TR))*(TRAT**((GAMMA-2.)/(
  1GAMMA-1.)))*(((TR/TRAT)+198.6)/(TR+198.6))
   RENO=12.*RENOU*SL*PC
   DELTA=.645*SL/SQRTF(RENO)
   IF(CN-6.5)42,42,43
```

```
42 DELSTR=DELTA*(-.00022*CN**6+.00671*CN**5-.07610*CN**4+.39770*CN**3
  1-.30876*CN**2+.99230*CN+2.28324)
   GO TO 48
43 IF(CN-7.5)44,44,45
44 DELSTR=DELTA*(8.6*CN-25.9)
   GO TO 48
45 IF(CN-9.0)46,46,47
46 DELSTR=DELTA*(10.0*CN-36.4)
   GO TO 48
47 DELSTR=DELTA*(10.9*CN-44.4)
48 REEFF=RE-DELSTR
   IF(REEFF)76,76,49
49 ARITER=(REEFF*REEFF)/(RT*RT)
   IF(SENSE SWITCH 2)50,52
50 PRINT 51,ARTERO,ARITER,IN3
51 FORMAT(2X8HARTERO =,E15.8,5X8HARITER =,E15.8,5X5HIN3 =,I5)
52 IF(ABSF(ARTERO-ARITER)-EPS3)57,57,53
53 IF(MAX3-IN3)55,55,54
54 ARTERO=(ARTERO+ARITER)/2.
   GO TO 33
55 PRINT 56,ARITER
56 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X12HAE/AT(DIV) =,E15.8)
57 SIGEFF=ATANF(REEFF/SL)
   PE=PO*((1.+(((GAMMA-1.)/2.)*(  **CN))**(-GAMMA/(GAMMA-1.)))
   TE=TR/TRAT
   CE=SQRT(GO*GAMMA*R*TE)
   VE=CE*CN
   VEF=VE/12.
   CFP=PE*ARITER*GO*AT/(WODOT*VE)
   FP=(1.-.5*(1.+COSF(SIGEFF)))/(1.+CFP)
   FDEL=2.*(RE-(DELTA/2.))*DELTA/((RE-DELSTR)*(RE-DELSTR))
   FMAX=PC*AT*SQRTF(2.*GAMMA*GAMMA*((2./(GAMMA+1.))**FGAM)/(GAMMA-1.)
  1)
   CF=SQRTF(((2.*GAMMA*GAMMA)/(GAMMA-1.))*((2./(GAMMA+1.))**FGAM)*(1.
  1-((PE/PC)**((GAMMA-1.)/GAMMA))))+((PE-PA)*ARITER/PC)
   FTHEOR=CF*PC*AT
   FN=(FMAX-FTHEOR)/FMAX
   FLTOT=1.-((1.-FP)*(1.-FDEL)*(1.-FN))
   FLTOTP=FLTOT*100.
   FNET=FMAX*(1.-FLTOT)
   PRINT 58,FNET,PRAT,DELP,WODOT,DT,FLTOTP,CN
58 FORMAT(2X,F8.5,5X,F7.4,5X,F9.5,5X,E15.8,5X,F7.4,5X,F6.2,5X,F7.3)
   IF(SENSE SWITCH 3)59,67
59 PRINT 60,WTDOT,IN2
60 FORMAT(2X7HWTDOT =,E15.8,5X5HIN2 =,I5)
   PRINT 61,ARTERO,ARITER,IN3
61 FORMAT(2X8HARTERO =,E15.8,5X8HARITER =,E15.8,5X5HIN3 =,I5)
   PRINT 62,PC,PE,TE,CE,VEF
62 FORMAT(2X4HPC =,E15.8,5X4HPE =,E15.8,5X4HTE =,E15.8,5X4HCE =,E15.8
  1,5X5HVEF =,E15.8)
   PRINT 63,TRAT,UO,RENOU,RENO
63 FORMAT(2X6HTRAT =,E15.8,5X4HUO =,E15.8,5X7HRENOU =,E15.8,5X6HRENO
  1=,E15.8)
   PRINT 64,DELTA,DELSTR,REEFF
64 FORMAT(2X7HDELTA =,E15.8,5X8HDELSTR =,E15.8,5X7HREEFF =,E15.8)
   PRINT 65,FTHEOR,FMAX
65 FORMAT(2X8HFTHEOR =,E15.8,5X6HFMAX =,E15.8)
   PRINT 66,FP,FDEL,FN,FLTOT
66 FORMAT(2X4HFP =,E15.8,5X6HFDEL =,E15.8,5X4HFN =,E15.8,5X7HFLTOT =,
```

```
  1E15.8)
67 IN3=0
   IF(FNETMX-FNET)75,75,68
68 IF(FNET-FNETMN)75,75,69
69 IF(PRATMX-PRAT)75,75,70
70 IF(PRAT-PRATMN)75,75,71
71 IF(I-1)74,72,74
72 IF(J-2)74,73,74
73 PAUSE
74 CALL PLOT(90,PRAT,FNET)
75 DT=DT+((DTMAX-DTMIN)/FLOAT(N3)
76 CONTINUE
   CALL PLOT(99)
77 CONTINUE
   END
```

VIII. Initial Conditions for Fig. 8

The following data are common to all the output data sheets for Fig. 8:

Valve inlet pressure = 15 psi

Nozzle area ratio = 50

Nozzle half-angle = 25 deg

Gas inlet temperature = 25°C

Nitrogen propellant

Output data for Fig. 8 (AOCR = 0.005)

FNET (LB)	PRAT	DELP (PSI)	WODOT (LB/SEC)	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9996	.00541	.66473497E-05	.0050	10.84	5.555
.00068	.9992	.01124	.95713649E-05	.0060	10.75	5.584
.00093	.9986	.02081	.13017524E-04	.0070	10.68	5.606
.00121	.9976	.03549	.16987863E-04	.0080	10.63	5.624
.00153	.9962	.05675	.21464957E-04	.0090	10.59	5.640
.00189	.9942	.08634	.26446876E-04	.0100	10.56	5.652
.00228	.9915	.12610	.31915156E-04	.0110	10.53	5.664
.00271	.9881	.17801	.37849123E-04	.0120	10.51	5.673
.00317	.9837	.24418	.44222242E-04	.0130	10.49	5.682
.00366	.9782	.32673	.50999725E-04	.0140	10.47	5.689
.00417	.9714	.42781	.58142313E-04	.0150	10.46	5.696
.00471	.9633	.54953	.65600542E-04	.0160	10.45	5.702
.00526	.9537	.69386	.73317386E-04	.0170	10.43	5.707
.00583	.9424	.86258	.81227063E-04	.0180	10.42	5.711
.00641	.9295	1.05721	.89257188E-04	.0190	10.41	5.715
.00699	.9147	1.27891	.97327252E-04	.0200	10.40	5.719
.00756	.8981	1.52845	.10535178E-03	.0210	10.39	5.721
.00813	.8795	1.80610	.11324126E-03	.0220	10.38	5.724
.00868	.8592	2.11162	.12090388E-03	.0230	10.37	5.726
.00921	.8370	2.44422	.12824856E-03	.0240	10.36	5.727
.00971	.8131	2.80255	.13518710E-03	.0250	10.35	5.728
.01018	.7876	3.18474	.14163682E-03	.0260	10.33	5.729
.01060	.7607	3.58841	.14752320E-03	.0270	10.31	5.729
.01098	.7326	4.01074	.15278169E-03	.0280	10.29	5.729
.01132	.7034	4.44856	.15735959E-03	.0290	10.26	5.729
.01160	.6734	4.89850	.16121801E-03	.0300	10.23	5.728
.01183	.6428	5.35700	.16433160E-03	.0310	10.19	5.727
.01200	.6119	5.82044	.16668911E-03	.0320	10.14	5.725
.01213	.5809	6.28530	.16829292E-03	.0330	10.09	5.723
.01220	.5501	6.74817	.16915825E-03	.0340	10.02	5.721
.01222	.5196	7.20591	.16931169E-03	.0350	9.94	5.718
.01220	.4896	7.65562	.16878958E-03	.0360	9.85	5.715
.01213	.4603	8.09476	.16763615E-03	.0370	9.74	5.712
.01202	.4319	8.52114	.16590186E-03	.0380	9.62	5.708
.01187	.4044	8.93294	.16364127E-03	.0390	9.47	5.704
.01170	.3780	9.32871	.16091159E-03	.0400	9.31	5.700
.01149	.3528	9.70734	.15777089E-03	.0410	9.11	5.695
.01127	.3287	10.06807	.15427689E-03	.0420	8.89	5.690
.01102	.3059	10.41042	.15048572E-03	.0430	8.64	5.685
.01076	.2843	10.73419	.14645100E-03	.0440	8.35	5.679
.01048	.2640	11.03940	.14222324E-03	.0450	8.02	5.674
.01020	.2449	11.32630	.13784927E-03	.0460	7.66	5.667
.00991	.2269	11.59526	.13337194E-03	.0470	7.24	5.661
.00963	.2102	11.84681	.12883001E-03	.0480	6.77	5.654
.00934	.1945	12.08158	.12425809E-03	.0490	6.25	5.647
.00905	.1799	12.30034	.11968518E-03	.0500	5.66	5.640

Output data for Fig. 8 (AOCR = 0.010)

FNET (LB)	PRAT	DELP (PSI)	WODOT (LB/SEC)	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9999	.00135	.66518464E-05	.0050	10.84	5.555
.00068	.9998	.00281	.95774389E-05	.0060	10.75	5.584
.00093	.9996	.00521	.13035394E-04	.0070	10.68	5.606
.00121	.9994	.00888	.17015620E-04	.0080	10.63	5.624
.00154	.9990	.01422	.21527372E-04	.0090	10.59	5.640
.00190	.9985	.02167	.26565605E-04	.0100	10.56	5.653
.00230	.9978	.03171	.32121287E-04	.0110	10.53	5.664
.00274	.9970	.04488	.38195162E-04	.0120	10.51	5.674
.00321	.9958	.06174	.44769545E-04	.0130	10.49	5.683
.00372	.9944	.08294	.51847249E-04	.0140	10.47	5.691
.00426	.9927	.10912	.59414308E-04	.0150	10.46	5.698
.00484	.9906	.14098	.67455684E-04	.0160	10.44	5.705
.00545	.9880	.17924	.75955145E-04	.0170	10.43	5.710
.00609	.9850	.22464	.84892876E-04	.0180	10.42	5.716
.00676	.9814	.27795	.94245469E-04	.0190	10.41	5.720
.00747	.9773	.33992	.10398889E-03	.0200	10.40	5.725
.00819	.9725	.41130	.11408861E-03	.0210	10.40	5.729
.00894	.9671	.49285	.12451212E-03	.0220	10.39	5.732
.00971	.9609	.58529	.13522265E-03	.0230	10.38	5.736
.01050	.9540	.68927	.14617407E-03	.0240	10.38	5.739
.01130	.9463	.80544	.15732183E-03	.0250	10.37	5.742
.01211	.9377	.93433	.16861365E-03	.0260	10.36	5.744
.01293	.9282	1.07643	.17999654E-03	.0270	10.36	5.746
.01375	.9178	1.23213	.19141197E-03	.0280	10.35	5.749
.01457	.9065	1.40169	.20279927E-03	.0290	10.35	5.750
.01539	.8943	1.58529	.21409652E-03	.0300	10.34	5.752
.01619	.881	1.78294	.22523901E-03	.0310	10.33	5.753
.01698	.8670	1.99456	.23616217E-03	.0320	10.33	5.755
.01774	.8520	2.21992	.24680109E-03	.0330	10.32	5.756
.01848	.8360	2.45863	.25709200E-03	.0340	10.31	5.757
.01920	.8193	2.71018	.26697294E-03	.0350	10.30	5.757
.01988	.8017	2.97394	.27638475E-03	.0360	10.29	5.758
.02052	.7833	3.24912	.28527238E-03	.0370	10.28	5.758
.02112	.7643	3.53482	.29358481E-03	.0380	10.26	5.758
.02168	.7446	3.83007	.30127666E-03	.0390	10.25	5.758
.02219	.7244	4.13376	.30830830E-03	.0400	10.23	5.758
.02265	.7036	4.44473	.31464642E-03	.0410	10.21	5.758
.02306	.6825	4.76178	.32026447E-03	.0420	10.19	5.757
.02342	.6610	5.08365	.32514335E-03	.0430	10.16	5.757
.02372	.6393	5.40905	.32927048E-03	.0440	10.13	5.756
.02397	.6175	5.73673	.33264043E-03	.0450	10.10	5.755
.02417	.5956	6.06543	.33525488E-03	.0460	10.06	5.754
.02432	.5737	6.39393	.33712159E-03	.0470	10.02	5.752
.02441	.5519	6.72105	.33825471E-03	.0480	9.97	5.751
.02446	.5302	7.04568	.33867361E-03	.0490	9.92	5.749
.02445	.5088	7.36678	.33840278E-03	.0500	9.86	5.748

Output data for Fig. 8 (AOCR = 0.015)

FNET (LB)	PRAT	DELP (PSI)	WOBOT (LB/SEC)	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9999	.00060	.66777189E-05	.0050	10.84	5.555
.00068	.9999	.00124	.95647662E-05	.0060	10.75	5.584
.00093	.9998	.00231	.13033916E-04	.0070	10.68	5.606
.00121	.9997	.00395	.17033480E-04	.0080	10.63	5.625
.00154	.9995	.00632	.21543401E-04	.0090	10.59	5.640
.00190	.9993	.00964	.26584054E-04	.0100	10.56	5.653
.00230	.9990	.01411	.32160187E-04	.0110	10.53	5.665
.00274	.9986	.01998	.38260065E-04	.0120	10.51	5.675
.00322	.9981	.02750	.44875056E-04	.0130	10.49	5.683
.00373	.9975	.03697	.52009147E-04	.0140	10.47	5.691
.00428	.9967	.04869	.59661191E-04	.0150	10.46	5.699
.00486	.9958	.06297	.67818546E-04	.0160	10.44	5.705
.00549	.9946	.08015	.76462925E-04	.0170	10.43	5.711
.00614	.9932	.10062	.85606490E-04	.0180	10.42	5.716
.00684	.9916	.12472	.95226658E-04	.0190	10.41	5.721
.00756	.9898	.15286	.10531547E-03	.0200	10.40	5.726
.00832	.9876	.18542	.11585490E-03	.0210	10.40	5.730
.00911	.9851	.22282	.12683085E-03	.0220	10.39	5.734
.00993	.9823	.26547	.13822301E-03	.0230	10.38	5.738
.01077	.9790	.31378	.15001033E-03	.0240	10.38	5.741
.01165	.9754	.36817	.16216746E-03	.0250	10.37	5.744
.01255	.9713	.42905	.17467100E-03	.0260	10.36	5.747
.01347	.9668	.49681	.18748964E-03	.0270	10.36	5.750
.01441	.9618	.57185	.20059160E-03	.0280	10.35	5.752
.01537	.9563	.65453	.21394220E-03	.0290	10.35	5.755
.01635	.9503	.74520	.22750412E-03	.0300	10.35	5.757
.01734	.9437	.84418	.24123676E-03	.0310	10.34	5.759
.01833	.9365	.95176	.25509870E-03	.0320	10.34	5.761
.01934	.9287	1.06818	.26904264E-03	.0330	10.33	5.762
.02034	.9204	1.19365	.28302359E-03	.0340	10.33	5.764
.02135	.9114	1.32833	.29699153E-03	.0350	10.32	5.765
.02235	.9018	1.47233	.31089524E-03	.0360	10.32	5.767
.02334	.8916	1.62570	.32468317E-03	.0370	10.31	5.768
.02432	.8807	1.78844	.33830361E-03	.0380	10.31	5.769
.02529	.8692	1.96050	.35170282E-03	.0390	10.30	5.770
.02623	.8572	2.14175	.36482769E-03	.0400	10.30	5.771
.02716	.8445	2.33199	.37762570E-03	.0410	10.29	5.771
.02805	.8312	2.53099	.39004616E-03	.0420	10.28	5.772
.02892	.8174	2.73845	.40203901E-03	.0430	10.28	5.772
.02975	.8030	2.95398	.41355621E-03	.0440	10.27	5.773
.03054	.7881	3.17717	.42455333E-03	.0450	10.26	5.773
.03130	.7728	3.40754	.43498742E-03	.0460	10.25	5.773
.03201	.7570	3.64458	.44482024E-03	.0470	10.24	5.773
.03268	.7408	3.88770	.45401676E-03	.0480	10.22	5.773
.03330	.7242	4.13632	.46254589E-03	.0490	10.21	5.773
.03387	.7073	4.38978	.47038118E-03	.0500	10.19	5.773

Output data for Fig. 8 (AOCR = 0.020)

FNET (LB)	PRAT	DELP (PSI)	WODOT (LB/SEC)	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9999	.00033	.66135316E-05	.0050	10.84	5.555
.00068	.9999	.00070	.95694775E-05	.0060	10.75	5.584
.00093	.9999	.00130	.13044370E-04	.0070	10.68	5.606
.00121	.9998	.00222	.17041147E-04	.0080	10.63	5.625
.00154	.9997	.00356	.21554164E-04	.0090	10.59	5.640
.00190	.9996	.00542	.26589393E-04	.0100	10.56	5.653
.00230	.9994	.00794	.32176277E-04	.0110	10.53	5.665
.00274	.9992	.01124	.38276549E-04	.0120	10.51	5.675
.00322	.9989	.01548	.44914064E-04	130	10.49	5.684
.00373	.9986	.02081	.52063551E-04	.0140	10.47	5.692
.00428	.9981	.02742	.59748139E-04	.0150	10.46	5.699
.00487	.9976	.03548	.67936462E-04	.0160	10.44	5.705
.00550	.9969	.04519	.76651555E-04	.0170	10.43	5.711
.00616	.9962	.05676	.85863754E-04	.0180	10.42	5.717
.00686	.9953	.07041	.95583308E-04	.0190	10.41	5.722
.00759	.9942	.08634	.10579068E-03	.0200	10.40	5.726
.00836	.9930	.10483	.11648683E-03	.0210	10.40	5.731
.00917	.9915	.12610	.12766326E-03	.0220	10.39	5.735
.01000	.9899	.15041	.13930289E-03	.0230	10.38	5.738
.01087	.9881	.17802	.15139867E-03	.0240	10.38	5.742
.01178	.9860	.20918	.16393100E-03	.0250	10.37	5.745
.01271	.9837	.24417	.17688712E-03	.0260	10.36	5.748
.01367	.9811	.28327	.19025123E-03	.0270	10.36	5.751
.01466	.9782	.32673	.20400051E-03	.0280	10.35	5.754
.01567	.9750	.37482	.21811433E-03	.0290	10.35	5.756
.01671	.9714	.42781	.23256928E-03	.0300	10.35	5.759
.01778	.9676	.48597	.24734333E-03	.0310	10.34	5.761
.01886	.9633	.54954	.26240331E-03	.0320	10.34	5.763
.01996	.9587	.61875	.27772243E-03	.0330	10.33	5.765
.02108	.9537	.69386	.29326958E-03	.0340	10.33	5.767
.02221	.9483	.77507	.30900976E-03	.0350	10.33	5.768
.02336	.9424	.86258	.32490915E-03	.0360	10.32	5.770
.02451	.9362	.95658	.34092810E-03	.0370	10.32	5.771
.02567	.9295	1.05721	.35702867E-03	.0380	10.32	5.773
.02683	.9223	1.16462	.37316935E-03	.0390	10.31	5.774
.02799	.9147	1.27891	.38930896E-03	.0400	10.31	5.775
.02915	.9066	1.40017	.40540308E-03	.0410	10.31	5.776
.03030	.8981	1.52845	.42140718E-03	.0420	10.30	5.777
.03145	.8890	1.66376	.43727648E-03	.0430	10.30	5.778
.03258	.8795	1.80609	.45296454E-03	.0440	10.29	5.779
.03369	.8696	1.95541	.46842645E-03	.0450	10.29	5.780
.03478	.8592	2.11161	.48361509E-03	.0460	10.28	5.781
.03586	.8483	2.27459	.49848536E-03	.0470	10.28	5.781
.03690	.8370	2.44421	.51299398E-03	.0480	10.27	5.782
.03792	.8253	2.62027	.52709516E-03	.0490	10.27	5.782
.03890	.8131	2.80254	.54074771E-03	.0500	10.26	5.782

Output data for Fig. 8 (AOCR = 0.030)

FNET (LB)	PRAT	DELP (PSI)	WODOT (LB/SEC.	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9999	.00016	.70147659E-05	.0050	10.84	5.555
.00068	.9999	.00031	.96052955E-05	.0060	10.75	5.584
.00093	.9999	.00057	.13064449E-04	.0070	10.68	5.606
.00121	.9999	.00099	.17047160E-04	.0080	10.63	5.625
.00154	.9998	.00158	.21548269E-04	.0090	10.59	5.640
.00190	.9998	.00241	.26593207E-04	.0100	10.56	5.653
.00230	.9997	.00353	.32188342E-04	.0110	10.53	5.665
.00274	.9996	.00499	.38292394E-04	.0120	10.51	5.675
.00322	.9995	.00688	.44936271E-04	.0130	10.49	5.684
.00374	.9993	.00925	.52103688E-04	.0140	10.47	5.692
.00429	.9991	.01220	.59810039E-04	.0150	10.46	5.699
.00488	.9989	.01578	.68027857E-04	.0160	10.44	5.705
.00551	.9986	.02011	.76769952E-04	.0170	10.43	5.711
.00617	.9983	.02527	.86051292E-04	.0180	10.42	5.717
.00688	.9979	.03136	.95831020E-04	.0190	10.41	5.722
.00762	.9974	.03849	.10613237E-03	.0200	10.40	5.727
.00840	.9968	.04676	.11694251E-03	.0210	10.40	5.731
.00921	.9962	.05629	.12826898E-03	.0220	10.39	5.735
.01006	.9955	.06720	.14009307E-03	.0230	10.38	5.739
.01095	.9946	.07962	.15241498E-03	.0240	10.38	5.742
.01187	.9937	.09365	.16522358E-03	.0250	10.37	5.746
.01282	.9927	.10944	.17850463E-03	.0260	10.36	5.749
.01381	.9915	.12713	.19226920E-03	.0270	10.36	5.752
.01484	.9902	.14687	.20650473E-03	.0280	10.35	5.755
.01589	.9887	.16876	.22118914E-03	.0290	10.35	5.757
.01698	.9871	.19298	.23631926E-03	.0300	10.35	5.760
.01810	.9853	.21966	.25188088E-03	.0310	10.34	5.762
.01925	.9834	.24894	.26786048E-03	.0320	10.34	5.764
.02043	.9812	.28098	.28424452E-03	.0330	10.34	5.767
.02164	.9789	.31592	.30101701E-03	.0340	10.33	5.769
.02287	.9764	.35391	.31815757E-03	.0350	10.33	5.770
.02413	.9736	.39509	.33565322E-03	.0360	10.33	5.772
.02541	.9706	.43961	.35347803E-03	.0370	10.32	5.774
.02672	.9674	.48760	.37161535E-03	.0380	10.32	5.776
.02804	.9640	.53921	.39003914E-03	.0390	10.32	5.777
.02939	.9603	.59456	.40872622E-03	.0400	10.31	5.779
.03075	.9564	.65378	.42765238E-03	.0410	10.31	5.780
.03213	.9521	.71700	.44678924E-03	.0420	10.31	5.781
.03352	.9477	.78433	.46611132E-03	.0430	10.31	5.783
.03492	.9429	.85587	.48558754E-03	.0440	10.30	5.784
.03633	.9378	.93173	.50518604E-03	.0450	10.30	5.785
.03775	.9325	1.01198	.52487623E-03	.0460	10.30	5.786
.03917	.9268	1.09672	.54462603E-03	.0470	10.30	5.787
.04059	.9209	1.18601	.56440021E-03	.0480	10.29	5.788
.04201	.9146	1.27989	.58416547E-03	.0490	10.29	5.789
.04343	.9081	1.37842	.60388334E-03	.0500	10.29	5.790

FNET (LB)	PRAT	DELP (PSI)	WODOT (LB/SEC)	DT (IN)	FLTOTP (PERCENT)	CN
.00047	.9999	.00005	.68546552E-05	.0050	10.84	5.555
.00068	.9999	.00011	.96939185E-05	.0060	10.75	5.584
.00093	.9999	.00021	.13233597E-04	.0070	10.68	5.606
.00121	.9999	.00035	.17167519E-04	.0080	10.63	5.625
.00154	.9999	.00056	.21477838E-04	.0090	10.59	5.640
.00190	.9999	.00086	.26627260E-04	.0100	10.56	5.653
.00230	.9999	.00127	.32215671E-04	.0110	10.53	5.665
.00274	.9998	.00179	.38329433E-04	.0120	10.51	5.675
.00322	.9998	.00248	.44991270E-04	.0130	10.49	5.684
.00374	.9997	.00333	.52154420E-04	.0140	10.47	5.692
.00429	.9997	.00439	.59852261E-04	.0150	10.46	5.699
.00488	.9996	.00568	.68090683E-04	.0160	10.44	5.705
.00551	.9995	.00724	.76833683E-04	.0170	10.43	5.711
.00618	.9993	.00911	.86149313E-04	.0180	10.42	5.717
.00689	.9992	.01130	.95936037E-04	.0190	10.41	5.722
.00763	.9990	.01387	.10630272E-03	.0200	10.40	5.727
.00841	.9988	.01686	.11718432E-03	.0210	10.40	5.731
.00923	.9986	.02031	.12858024E-03	.0220	10.39	5.735
.01009	.9983	.02425	.14049889E-03	.0230	10.38	5.739
.01098	.9980	.02875	.15292617E-03	.0240	10.38	5.743
.01192	.9977	.03383	.16587225E-03	.0250	10.37	5.746
.01288	.9973	.03957	.17935091E-03	.0260	10.36	5.749
.01389	.9969	.04600	.19333384E-03	.0270	10.36	5.752
.01493	.9964	.05318	.20780575E-03	.0280	10.35	5.755
.01601	.9959	.06117	.22280804E-03	.0290	10.35	5.758
.01712	.9953	.07001	.23829603E-03	.0300	10.35	5.760
.01827	.9946	.07977	.25427324E-03	.0310	10.34	5.763
.01946	.9939	.09052	.27075407E-03	.0320	10.34	5.765
.02068	.9931	.10230	.28770887E-03	.0330	10.34	5.767
.02193	.9923	.11518	.30514523E-03	.0340	10.33	5.770
.02322	.9913	.12923	.32305879E-03	.0350	10.33	5.772
.02454	.9903	.14450	.34141796E-03	.0360	10.33	5.773
.02590	.9892	.16106	.36024045E-03	.0370	10.32	5.775
.02728	.9880	.17899	.37951480E-03	.0380	10.32	5.777
.02870	.9867	.19835	.39923343E-03	.0390	10.32	5.779
.03015	.9853	.21920	.41937701E-03	.0400	10.32	5.780
.03163	.9838	.24162	.43994008E-03	.0410	10.31	5.782
.03314	.9822	.26567	.46091062E-03	.0420	10.31	5.783
.03468	.9805	.29142	.48227938E-03	.0430	10.31	5.785
.03624	.9787	.31893	.50401912E-03	.0440	10.31	5.786
.03783	.9767	.34828	.52613881E-03	.0450	10.31	5.788
.03945	.9746	.37954	.54860907E-03	.0460	10.30	5.789
.04109	.9724	.41276	.57142335E-03	.0470	10.30	5.790
.04276	.9701	.44802	.59455231E-03	.0480	10.30	5.791
.04444	.9676	.48538	.61799398E-03	.0490	10.30	5.792
.04615	.9650	.52490	.64172456E-03	.0500	10.30	5.793

IX. List Print for Fig. 9

```
      GAMMA=1.401
      PA=0.
      PI=3.1416
      R=55.16*12.
      GO=386.0677
      ARTGEO=50.
      SIGDEG=25.
      CV=4290.
      AOCR=.0015
      DT=.010
      TO=25.
      FREF=.0019063
      CNINIT=6.
      PRATIT=.95
      READ 1,POMIN,POMAX,POLEN,POINC,FPERMN,FPERMX,FPERLN,FPERIC
    1 FORMAT(2F10.5,F5.1,F10.5,2F10.7,F5.1,F10.7)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.0)
      XMIN=POMIN
      XMAX=POMAX
      XLEN=POLEN
      XINC=POINC
      YMIN=FPERMN
      YMAX=FPERMX
      YLEN=FPERLN
      YINC=FPERIC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 4 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    3 FORMAT(F4.0)
    4 DL=DL+1.
      DL=0.
      DO 6 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    5 FORMAT(F5.2)
    6 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,AOCR)
    7 FORMAT(9HAO X CR =,F7.4,1X2HIN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,DT)
    8 FORMAT(4HDT =,F6.3,1X2HIN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.5*YINC)))
      CALL CHAR(0,0.1,0)
    9 FORMAT(19HNITROGEN PROPELLANT)
```

```
      CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,ARTGEO)
   10 FORMAT(12H(AE/AT)GEO =,F5.1)
      CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,SIGDEG)
   11 FORMAT(7HSIGMA =,F5.1)
      CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.5*YINC)))
      CALL CHAR(1,0.1,0,FREF)
  111 FORMAT(6HFREF =,F10.7,1X3HLB.)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
     1))
      CALL CHAR(0,0.1,0)
   12 FORMAT(2HPO)
      CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
     1+.3)*YINC)))
      CALL CHAR(0,0.2,0)
   13 FORMAT(28HNET THRUST VS INLET PRESSURE)
      CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
     1C))/2.))
      CALL CHAR(0,0.1,1)
   14 FORMAT(27HNET THRUST/REFERENCE THRUST)
      N2=6
      N3=N2-1
      FLON3=N3
      MAX1=20
      MAX2=20
      MAX3=20
      EPS1=.001
      EPS2=.001
      EPS3=.001
      PRAT=PRATIT
      FGAM=(GAMMA+1.)/(GAMMA-1.)
      TR=(9.*TO/5.)+491.69
      PRINT 15,TO
   15 FORMAT(1H1,4X23HGAS INLET TEMPERATURE =,F6.1,1X5HDEG C)
      PRINT 150
  150 FORMAT(5X30HFREF=.0019063 LBS.  (PO=15PSI))
      PRINT 151
  151 FORMAT(5X14HFPER=FNET/FREF)
      PRINT 16,AOCR
   16 FORMAT(5X9HAO X CR =,F7.4,1X3HIN2)
      PRINT 17,DT
   17 FORMAT(5X24HNOZZLE THROAT DIAMETER =,F7.4,1X2HIN)
      PRINT 18,ARTGEO
   18 FORMAT(5X19HNOZZLE AREA RATIO =,F7.2)
      PRINT 19,SIGDEG
   19 FORMAT(5X19HNOZZLE HALF-ANGLE =,F5.1,1X3HDEG)
      PRINT 20
   20 FORMAT(///)
      PRINT 21
   21 FORMAT(1X7HPO(PSI),3X4HFPER,5X8HFNET(LB),4X8HFMAX(LB),2X7HPC(PSI),
     1 4X13HWODOT(LB/SEC),5X2HCN,/)
      RT=DT/2.
      AT=PI*(RT**2)
      AE=ARTGEO*AT
      RE=SQRTF(AE/PI)
      DE=RE*2.
      SIGMA=(SIGDEG/360.)*2.*PI
      SL=(RE-RT)*COSF(SIGMA)/SINF(SIGMA)
```

```
      PO=POMIN
      DO 59 I=1,N2
      CPC=((GAMMA-1.)/2.)*((AT/(AOCR))**2.)*((2./(GAMMA+1.))**FGAM)
      IN1=0
   22 FPRAT=(PRAT**((2.-(2.*GAMMA))/GAMMA))-(PRAT**((1.-GAMMA)/GAMMA))-C
     1PC
      DFPRAT=(((2.-(2.*GAMMA))/GAMMA)*(PRAT**((2.-(3.*GAMMA))/GAMMA)))-(
     1((1.-GAMMA)/GAMMA)*(PRAT**((1.-(2.*GAMMA))/GAMMA)))
      IN1=IN1+1
      PRATN=PRAT-(FPRAT/DFPRAT)
      IF(SENSE SWITCH 2)23,25
   23 PRINT 24,FPRAT,DFPRAT,PRATN,IN1
   24 FORMAT(2X7HFPRAT =,E15.8,5X8HDFPRAT =,E15.8,5X7HPRATN =,E15.8,5X5H
     1IN1 =,I4)
   25 IF(ABSF(PRATN-PRAT)-EPS1)29,29,26
   26 PRAT=PRATN
      IF(MAX1-IN1)27,27,22
   27 PRINT 28, PRAT
   28 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X12HPC/PO(DIV) =,E15.8)
   29 PRAT=PRATN
      PC=PRAT*PO
      RODOT=AOCR*PO*(PRAT**(1./GAMMA))*SQRTF((2.*GO/(R*TR))*(GAMMA/(GAMM
     1A-1.))*(1.-(PRAT**((GAMMA-1.)/GAMMA))))
      ARTERO=.5*ARTGEO
      CN=CNINIT
      IN3=0
   30 IN2=0
      IN3=IN3+1
      C1=(GAMMA+1.)/(2.*(GAMMA-1.))
      C2=(GAMMA-1.)/2.
      C3=((GAMMA+1.)/2.)**C1
   31 FCN=C3*CN*((1.+(C2*CN*CN))**(-C1))-(1./ARTERO)
      DFCN=C3*(2.*C2*CN*CN*(-C1)*((1.+(C2*CN*CN))**(-C1-1.))+((1.+(C2*CN
     1*CN))**(-C1)))
      CNN=CN-(FCN/DFCN)
      IN2=IN2+1
      IF(SENSE SWITCH 2)32,34
   32 PRINT 33,FCN,DFCN,CNN,IN2
   33 FORMAT(2X5HFCN =,E15.8,5X6HDFCN =,E15.8,5X5HCNN =,E15.8,5X5HIN2 =,
     1I4)
   34 IF(ABSF(CNN-CN)-EPS2)38,38,35
   35 CN=CNN
      IF(MAX2-IN2)36,36,31
   36 PRINT 37,CN
   37 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HME(DIV) =,E15.8)
   38 CN=CNN
      TRAT=1.+((GAMMA-1.)*CN*CN/2.)
      UO=(2.270E-08)*(TR**(3/2))/(TR+198.6)
      RENOU=(CN/UO)*SQRTF(GAMMA/((GAMMA-1.)*CV*TR))*(TRAT**((GAMMA-2.)/(
     1GAMMA-1.)))*(((TR/TRAT)+198.6)/(TR+198.6))
      RENO=12.*RENOU*SL*PC
      DELTA=.645*SL/SQRTF(RENO)
      IF(CN-6.5)39,39,40
   39 DELSTR=DELTA*(-.00022*CN**6+.00671*CN**5-.07610*CN**4+.39770*CN**3
     1-.30876*CN**2+.99230*CN+2.28324)
      GO TO 45
   40 IF(CN-7.5)41,41,42
   41 DELSTR=DELTA*(8.6*CN-25.9)
      GO TO 45
```

```
42 IF(CN-9.0)43,43,44
43 DELSTR=DELTA*(10.0*CN-36.4)
   GO TO 45
44 DELSTR=DELTA*(10.9*CN-44.4)
45 REEFF=RE-DELSTR
   IF(REEFF)58,58,46
46 ARITER=(REEFF**2)/(RT**2)
   IF(SENSE SWITCH 2)47,49
47 PRINT 48,ARTERO,ARITER,IN3
48 FORMAT(2X8HARTERO =,E15.8,5X8HARITER =,E15.8,5X5HIN3 =,I4)
49 IF(ABSF(ARTERO-ARITER)-EPS3)54,54,50
50 IF(MAX3-IN3)52,52,51
51 ARTERO=(ARTERO+ARITER)/2.
   GO TO 30
52 PRINT 53,ARITER
53 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X13HARTERO(DIV) =,E15.8)
54 SIGEFF=ATANF(REEFF/SL)
   PE=PO*((1.+(((GAMMA-1.)/2.)*CN*CN))**(-GAMMA/(GAMMA-1.)))
   TE=TR/TRAT
   CE=SQRTF(GO*GAMMA*R*TE)
   VE=CE*CN
   VEF=VE/12.
   CFP=PE*ARITER*GO*AT/(WODOT*VE)
   FP=(1.-.5*(1.+COSF(SIGEFF)))/(1.+CFP)
   FDEL=2.*(RE-(DELTA/2.))*DELTA/((RE-DELSTR)*(RE-DELSTR))
   FMAX=PC*AT*SQRTF(2.*GAMMA*GAMMA*((2./(GAMMA+1.))**FGAM)/(GAMMA-1.)
  1)
   CF=SQRTF(((2.*GAMMA*GAMMA)/(GAMMA-1.))*((2./(GAMMA+1.))**FGAM)*(1.
  1-((PE/PC)**((GAMMA-1.)/GAMMA))))+((PE-PA)*ARITER/PC)
   FTHEOR=CF*PC*AT
   FN=(FMAX-FTHEOR)/FMAX
   FLTOT=1.-((1.-FP)*(1.-FDEL)*(1.-FN))
   FNET=FMAX*(1.-FLTOT)
   FPER=FNET/FREF
   PRINT 55,PO,FPER,FNET,FMAX,PC,WODOT,CN
55 FORMAT(1X,F6.1,2X,F7.4,2X,F10.7,2X,F10.7,2X,F7.3,2X,E15.8,2X,F7.3)
   IN3=0
   IF(FPERMX-FPER)58,58,56
56 IF(FPER-FPERMN)58,58,57
57 CALL PLOT(90,PO,FPER)
58 PO=PO+((POMAX-POMIN)/FLON3)
59 CONTINUE
   CALL PLOT(99)
   END
```

X. Output Data for Fig. 9

GAS INLET TEMPERATURE = 25.0 DEG C
FREF=.0019063 LBS. (PO=15PSI)
FPER=FNET/FREF
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
NOZZLE AREA RATIO = 50.00
NOZZLE HALF-ANGLE = 25.0 DEG

PO(PSI)	FPER	FNET(LB)	FMAX(LB)	PC(PSI)	WODOT(LB/SEC)	CN
10.0	.6656	.0012688	.0014210	9.993	.17722703E-04	5.599
15.0	1.0000	.0019063	.0021315	14.990	.26591274E-04	5.653
20.0	1.3345	.0025439	.0028420	19.987	.35445406E-04	5.686
25.0	1.6690	.0031816	.0035525	24.983	.44306763E-04	5.709
30.0	2.0035	.0038193	.0042630	29.980	.53168111E-04	5.727
35.0	2.3380	.0044571	.0049735	34.977	.62029470E-04	5.740

XI. List Print for Fig. 10

```
      GAMMA=1.401
      PI=3.1416
      R=55.15*12.
      GO=386.0677
      PA=0.
      TO=25.
      PO=15.
      TR=(9.*TO/5.)+491.69
      CV=4290.
      AOCR=.0015
      DT=.010
      SIGMIN=15.
      SIGMAX=40.
      CNINIT=6.
      PRATIT=.95
      READ 1,ARTGMN,ARTGMX,ARTGLN,APTGIC,FPERMN,FPERMX,FPERLN,FPERIC
    1 FORMAT(2F10.5,F5.1,F10.5,2F10.7,F5.1,F10.7)
      READ 2,DX,DY,DLX,DLY,DLT,DP,XSF,YSF
    2 FORMAT(6F5.1,2F10.0)
      XMIN=ARTGMN
      XMAX=ARTGMX
      XLEN=ARTGLN
      XINC=ARTGIC
      YMIN=FPERMN
      YMAX=FPERMX
      YLEN=FPERLN
      YINC=FPERIC
      DIMENSION XL(6),YL(8)
      XL(1)=XMIN*XSF
      YL(1)=YMIN*YSF
      XPOSX=XMIN-((DX/2.)*.1*XINC)
      YPOSX=YMIN-(.2*YINC)
      XPOSY=XMIN-((DY+1.)*.1*XINC)
      YPOSY=YMIN-(.05*YINC)
      CALL PLOT(101,XMIN,XMAX,XLEN,XINC,YMIN,YMAX,YLEN,YINC)
      DO 1000 ICAN=1,5
 1000 XL(ICAN+1)=XL(ICAN)+(XINC*XSF)
      DO 1001 JCAN=1,7
 1001 YL(JCAN+1)=YL(JCAN)+(YINC*YSF)
      DL=0.
      DO 4 ICAN=1,6
      CALL PLOT(90,(XPOSX+(DL*XINC)),YPOSX)
      CALL CHAR(1,0.1,0,XL(ICAN))
    3 FORMAT(F5.0)
    4 DL=DL+1.
      DL=0.
      DO 6 JCAN=1,8
      CALL PLOT(90,XPOSY,(YPOSY+(DL*YINC)))
      CALL CHAR(1,0.1,0,YL(JCAN))
    5 FORMAT(F5.2)
    6 DL=DL+1.
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.1*YINC)))
      CALL CHAR(1,0.1,0,AOCR)
    7 FORMAT(9HAO X CR =,F7.5,1X2HIN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.3*YINC)))
      CALL CHAR(1,0.1,0,DT)
    8 FORMAT(4HDT =,F6.3,1X2HIN)
      CALL PLOT(90,(XMIN+(.5*XINC)),(YMAX+(.5*YINC)))
      CALL CHAR(0,0.1,0)
```

```
  9 FORMAT(19HNITROGEN PROPELLANT)
    CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.1*YINC)))
    CALL CHAR(1,0.1,0,PO)
 10 FORMAT(4HPO =,F6.2,1X6HLBS/IN)
    CALL PLOT(90,(XMIN+(3.*XINC)),(YMAX+(.3*YINC)))
    CALL CHAR(1,0.1,0,TO)
 11 FORMAT(4HTO =,F6.2,1X1HC)
    CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLX*.1*XINC))/2.)),(YMIN-(.5*YINC)
   1))
    CALL CHAR(0,0.1,0)
 12 FORMAT(10H(AE/AT)GEO)
    CALL PLOT(90,(XMIN+((XMAX-XMIN-(DLT*.2*XINC))/2.)),(YMAX+(((.2*DP)
   1+.3)*YINC)))
    CALL CHAR(0,0.2,0)
 13 FORMAT(31HNET THRUST VS NOZZLE AREA RATIO)
    CALL PLOT(90,(XMIN-((DY+2.)*.1*XINC)),(YMIN+(YMAX-YMIN-(DLY*.1*YIN
   1C))/2.))
    CALL CHAR(0,0.1,1)
 14 FORMAT(25HNET THRUST/MAXIMUM THRUST)
    N1=6
    N2=51
    N3=N2-1
    FLON3=N3
    N4=N1-1
    FLON4=N4
    MAX1=20
    MAX2=20
    MAX3=20
    EPS1=.001
    EPS2=.001
    EPS3=.001
    PRAT=PRATIT
    FGAM=(GAMMA+1.)/(GAMMA-1.)
    SIGDEG=SIGMIN
    DO 64 I=1,N1
    PRINT 15,SIGDEG
 15 FORMAT(1H1,4X19HNOZZLE HALF-ANGLE =,F5.1,1X3HDEG)
    PRINT 150
150 FORMAT(5X16HFPER = FNET/FMAX)
    PRINT 151
151 FORMAT(5X33H(AE/AT)GEO = GEOMETRIC AREA RATIO)
    PRINT 16,AOCR
 16 FORMAT(5X9HAO X CR =,F7.4,1X3HIN2)
    PRINT 17,DT
 17 FORMAT(5X24HNOZZLE THROAT DIAMETER =,F7.4,1X2HIN)
    PRINT 18,TO
 18 FORMAT(5X23HGAS INLET TEMPERATURE =,F6.1,1X5HDEG C ///)
    PRINT 19
 19 FORMAT(4X4HFPER,7X6HARTGEO,8X4HFNET,9X4HFMAX)
    PRINT 190
190 FORMAT(29X4H(LB),9X4H(LB),/)
    RT=DT/2.
    AT=PI*(RT**2)
    SIGMA=(SIGDEG/360.)*2.*PI
    ARTGEO=ARTGMN
    DO 63 J=1,N2
    AE=ARTGEO*AT
    RE=SQRTF(AE/PI)
    DE=RE*2.
```

```
   SL=(RE-RT)*COSF(SIGMA)/SINF(SIGMA)
   CPC=((GAMMA-1.)/2.)*((AT/(AOCR))**2.)*((2./(GAMMA+1.))**FGAM1
   IN1=0
20 FPRAT=(PRAT**((2.-(2.*GAMMA))/GAMMA))-(PRAT**((1.-GAMMA)/GAMMA))-C
  1PC
   DFPRAT=(((2.-(2.*GAMMA))/GAMMA)*(PRAT**((2.-(3.*GAMMA))/GAMMA)))-(
  1((1.-GAMMA)/GAMMA)*(PRAT**((1.-(2.*GAMMA))/GAMMA)))
   IN1=IN1+1
   PRATN=PRAT-(FPRAT/DFPRAT)
   IF(SENSE SWITCH 2)21,23
21 PRINT 22,FPRAT,DFPRAT,PRATN,IN1
22 FORMAT(2X7HFPRAT =,E15.8,5X8HDFPRAT =,E15.8,5X7HPRATN =,E15.8,5X5H
  1IN1 =,I4)
23 IF(ABSF(PRATN-PRAT)-EPS1)27,27,24
24 PRAT=PRATN
   IF(MAX1-IN1)25,25,20
25 PRINT 26,PRAT
26 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X12HPC/PO(DIV) =,E15.8)
27 PRAT=PRATN
   PC=PRAT*PO
   WODOT=AOCR*PO*(PRAT**(1./GAMMA))*SQRTF((2.*GO/(R*TR))*(GAMMA/(GAMM
  1A-1.))*(1.-(PRAT**((GAMMA-1.)/GAMMA))))
   ARTERO=.5*ARTGEO
   CN=CNINIT
   IN3=0
28 IN2=0
   IN3=IN3+1
   C1=(GAMMA+1.)/(2.*(GAMMA-1.))
   C2=(GAMMA-1.)/2.
   C3=((GAMMA+1.)/2.)**C1
29 FCN=C3*CN*((1.+(C2*CN*CN))**(-C1))-(1./ARTERO)
   DFCN=C3*(2.*C2*CN*CN*(-C1)*((1.+(C2*CN*CN))**(-C1-1.))+((1.+(C2*CN
  1*CN))**(-C1)))
   CNN=CN-(FCN/DFCN)
   IN2=IN2+1
   IF(SENSE SWITCH 2)30,32
30 PRINT 31,FCN,DFCN,CNN,IN2
31 FORMAT(2X5HFCN =,E15.8,5X6HDFCN =,E15.8,5X5HCNN =,E15.8,5X5HIN2 =,
  1I4)
32 IF(ABSF(CNN-CN)-EPS2)36,36,33
33 CN=CNN
   IF(MAX2-IN2)34,34,29
34 PRINT 35,CN
35 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HME(DIV) =,F15.8)
36 CN=CNN
   TRAT=1.+((GAMMA-1.)*CN*CN/2.)
   UO=(2.270E-08)*(TR**(3./2.))/(TR+198.6)
   RENOU=(CN/UO)*SQRTF(GAMMA/((GAMMA-1.)*CV*TR))*(TRAT**((GAMMA-2.)/(
  1GAMMA-1.)))*(((TR/TRAT)+198.6)/(TR+198.6))
   RENO=12.*RENOU*SL*PC
   DELTA=.645*SL/SQRTF(RENO)
   IF(CN-6.5)37,37,38
37 DELSTR=DELTA*(-.00022*CN**6+.00671*CN**5-.07610*CN**4+.39770*CN**3
  1-.30876*CN**2+.99230*CN+2.28324)
   GO TO 43
38 IF(CN-7.5)39,39,40
39 DELSTR=DELTA*(8.6*CN-25.9)
   GO TO 43
40 IF(CN-9.0)41,41,42
```

```
'1 DELSTR=DELTA*(10.0*CN-36.4)
   GO TO 43
42 DELSTR=DELTA*(10.9*CN-44.4)
43 IF(SENSE SWITCH 2)44,46
44 PRINT 45,RENO,RE,SL
45 FORMAT(2X6HRENO =,E15.8,5X4HRE =,E15.8,5X4HSL =,E15.8)
46 REEFF=RE-DELSTR
   IF(REEFF)62,62,47
47 ARITER=(REEFF**2)/(RT**2)
   IF(SENSE SWITCH 2)48,50
48 PRINT 49,ARTERO,ARITER,IN3
49 FORMAT(2X8HARTERO =,E15.8,5X8HARITER =,E15.8,5X5HIN3 =,I4)
50 IF(ABSF(ARTERO-ARITER)-EPS3)55,55,51
51 IF(MAX3-IN3)53,53,52
52 ARTERO=(ARTERO+ARITER)/2.
   GO TO 28
53 PRINT 54,ARITER
54 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X13HARTERO(DIV) =,E15.8)
55 SIGEFF=ATANF(REEFF/SL)
   PE=PO*((1.+(((GAMMA-1.)/2.)*CN*CN))**(-GAMMA/(GAMMA-1.)))
   TE=TR/TRAT
   CE=SQRTF(GO*GAMMA*R*TE)
   VE=CE*CN
   CFP=PE*ARITER*GO*AT/(WDOT*VE)
   FP=(1.-.5*(1.+COSF(SIGEFF)))/(1.+CFP)
   FDEL=2.*(RE-(DELTA/2.))*DELTA/((RE-DELSTR)*(RE-DELSTR))
   FMAX=PC*AT*SQRTF(2.*GAMMA*GAMMA*((2./(GAMMA+1.))**FGAM)/(GAMMA-1.)
  1)
   CF=SQRTF(((2.*GAMMA*GAMMA)/(GAMMA-1.))*((2./(GAMMA+1.))**FGAM)*(1.
  1-((PE/PC)**((GAMMA-1.)/GAMMA))))+((PE-PA)*ARITER/PC)
   FTHEOR=CF*PC*AT
   FN=(FMAX-FTHEOR)/FMAX
   FLTOT=1.-((1.-FP)*(1.-FDEL)*(1.-FN))
   FNET=FMAX*(1.-FLTOT)
   FPER=FNET/FMAX
   IN3=0
   PRINT 56,FPER,ARTGEO,FNET,FMAX
56 FORMAT(2X,F8.5,5X,F7.1,5X,F8.5,5X,F8.5)
   IF(FPERMX-FPER)62,62,57
57 IF(FPER-FPERMN)62,62,58
58 IF(I-1)61,59,61
59 IF(J-2)61,60,61
60 PAUSE
61 CALL PLOT(90,ARTGEO,FPER)
62 ARTGEO=ARTGEO+((ARTGMX-ARTGMN)/FLON3)
63 CONTINUE
   CALL PLOT(99)
   SIGDEG=SIGDEG+((SIGMAX-SIGMIN)/FLON4)
64 CONTINUE
   END
```

XII. Output Data for Fig. 10

NOZZLE HALF-ANGLE = 15.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.82871	25.0	.00176	.00213
.82976	30.0	.00176	.00213
.83017	35.0	.00176	.00213
.83018	40.0	.00176	.00213
.82992	45.0	.00176	.00213
.82949	50.0	.00176	.00213
.82893	55.0	.00176	.00213
.82828	60.0	.00176	.00213
.82758	65.0	.00176	.00213
.82682	70.0	.00176	.00213
.82604	75.0	.00176	.00213
.82523	80.0	.00175	.00213
.82440	85.0	.00175	.00213
.82356	90.0	.00175	.00213
.82272	95.0	.00175	.00213
.82187	100.0	.00175	.00213
.82102	105.0	.00175	.00213
.82018	110.0	.00174	.00213
.81933	115.0	.00174	.00213
.81849	120.0	.00174	.00213
.81765	125.0	.00174	.00213
.81681	130.0	.00174	.00213
.81598	135.0	.00173	.00213
.81515	140.0	.00173	.00213
.81433	145.0	.00173	.00213
.81352	150.0	.00173	.00213
.81271	155.0	.00173	.00213
.81191	160.0	.00173	.00213
.81112	165.0	.00172	.00213
.81033	170.0	.00172	.00213
.80955	175.0	.00172	.00213
.80877	180.0	.00172	.00213
.80801	185.0	.00172	.00213
.80724	190.0	.00172	.00213
.80649	195.0	.00171	.00213
.80574	200.0	.00171	.00213
.80500	205.0	.00171	.00213
.80426	210.0	.00171	.00213
.80353	215.0	.00171	.00213
.80280	220.0	.00171	.00213
.80208	225.0	.00170	.00213
.80137	230.0	.00170	.00213
.80066	235.0	.00170	.00213
.79996	240.0	.00170	.00213
.79926	245.0	.00170	.00213
.79857	250.0	.00170	.00213
.79788	255.0	.00170	.00213
.79720	260.0	.00169	.00213
.79652	265.0	.00169	.00213
.79585	270.0	.00169	.00213
.79519	275.0	.00169	.00213

NOZZLE HALF-ANGLE = 20.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
A0 X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.83575	25.0	.00178	.00213
.83855	30.0	.00178	.00213
.84044	35.0	.00179	.00213
.84173	40.0	.00179	.00213
.84262	45.0	.00179	.00213
.84322	50.0	.00179	.00213
.84362	55.0	.00179	.00213
.84385	60.0	.00179	.00213
.84396	65.0	.00179	.00213
.84397	70.0	.00179	.00213
.84391	75.0	.00179	.00213
.84378	80.0	.00179	.00213
.84360	85.0	.00179	.00213
.84339	90.0	.00179	.00213
.84313	95.0	.00179	.00213
.84286	100.0	.00179	.00213
.84255	105.0	.00179	.00213
.84223	110.0	.00179	.00213
.84189	115.0	.00179	.00213
.84154	120.0	.00179	.00213
.84118	125.0	.00179	.00213
.84081	130.0	.00179	.00213
.84042	135.0	.00179	.00213
.84004	140.0	.00179	.00213
.83964	145.0	.00178	.00213
.33924	150.0	.00178	.00213
.83884	155.0	.00178	.00213
.83844	160.0	.00178	.00213
.83803	165.0	.00178	.00213
.83762	170.0	.00178	.00213
.83720	175.0	.00178	.00213
.83679	180.0	.00178	.00213
.83638	185.0	.00178	.00213
.83596	190.0	.00178	.00213
.83555	195.0	.00178	.00213
.83513	200.0	.00178	.00213
.83472	205.0	.00177	.00213
.83430	210.0	.00177	.00213
.83389	215.0	.00177	.00213
.83348	220.0	.00177	.00213
.83306	225.0	.00177	.00213
.83265	230.0	.00177	.00213
.83224	235.0	.00177	.00213
.83183	240.0	.00177	.00213
.83143	245.0	.00177	.00213
.83102	250.0	.00177	.00213
.83061	255.0	.00177	.00213
.83021	260.0	.00176	.00213
.82981	265.0	.00176	.00213
.82941	270.0	.00176	.00213
.82901	275.0	.00176	.00213

NOZZLE HALF-ANGLE = 25.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.83324	25.0	.00177	.00213
.83751	30.0	.00178	.00213
.84062	35.0	.00179	.00213
.84298	40.0	.00179	.00213
.84480	45.0	.00180	.00213
.84623	50.0	.00180	.00213
.84738	55.0	.00180	.00213
.84830	60.0	.00180	.00213
.84905	65.0	.00180	.00213
.84966	70.0	.00181	.00213
.85015	75.0	.00181	.00213
.85055	80.0	.00181	.00213
.85087	85.0	.00181	.00213
.85112	90.0	.00181	.00213
.85132	95.0	.00181	.00213
.85147	100.0	.00181	.00213
.85158	105.0	.00181	.00213
.85165	110.0	.00181	.00213
.85169	115.0	.00181	.00213
.85170	120.0	.00181	.00213
.85169	125.0	.00181	.00213
.85165	130.0	.00181	.00213
.85160	135.0	.00181	.00213
.85153	140.0	.00181	.00213
.85144	145.0	.00181	.00213
.85135	150.0	.00181	.00213
.85124	155.0	.00181	.00213
.85112	160.0	.00181	.00213
.85099	165.0	.00181	.00213
.85085	170.0	.00181	.00213
.85070	175.0	.00181	.00213
.85054	180.0	.00181	.00213
.85038	185.0	.00181	.00213
.85021	190.0	.00181	.00213
.85004	195.0	.00181	.00213
.84987	200.0	.00181	.00213
.84968	205.0	.00181	.00213
.84950	210.0	.00181	.00213
.84931	215.0	.00181	.00213
.84911	220.0	.00180	.00213
.84892	225.0	.00180	.00213
.84872	230.0	.00180	.00213
.84852	235.0	.00180	.00213
.84831	240.0	.00180	.00213
.84811	245.0	.00180	.00213
.84790	250.0	.00180	.00213
.84834	255.0	.00180	.00213
.84812	260.0	.00180	.00213
.84791	265.0	.00180	.00213
.84769	270.0	.00180	.00213
.84747	275.0	.00180	.00213

NOZZLE HALF-ANGLE = 30.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.82383	25.0	.00175	.00213
.82941	30.0	.00176	.00213
.83362	35.0	.00177	.00213
.83690	40.0	.00178	.00213
.83955	45.0	.00178	.00213
.84172	50.0	.00179	.00213
.84353	55.0	.00179	.00213
.84506	60.0	.00180	.00213
.84637	65.0	.00180	.00213
.84750	70.0	.00180	.00213
.84847	75.0	.00180	.00213
.84933	80.0	.00181	.00213
.85007	85.0	.00181	.00213
.85073	90.0	.00181	.00213
.85131	95.0	.00181	.00213
.85183	100.0	.00181	.00213
.85229	105.0	.00181	.00213
.85269	110.0	.00181	.00213
.85305	115.0	.00181	.00213
.85338	120.0	.00181	.00213
.85366	125.0	.00181	.00213
.85391	130.0	.00182	.00213
.85414	135.0	.00182	.00213
.85434	140.0	.00182	.00213
.85452	145.0	.00182	.00213
.85467	150.0	.00182	.00213
.85481	155.0	.00182	.00213
.85492	160.0	.00182	.00213
.85502	165.0	.00182	.00213
.85511	170.0	.00182	.00213
.85518	175.0	.00182	.00213
.85524	180.0	.00182	.00213
.85529	185.0	.0018	.00213
.85533	190.0	.0018	.00213
.85536	195.0	.00182	.00213
.85538	200.0	.00182	.00213
.85539	205.0	.00182	.00213
.85539	210.0	.00182	.00213
.85539	215.0	.00182	.00213
.85537	220.0	.00182	.00213
.85577	225.0	.00182	.00213
.85574	230.0	.00182	.00213
.85571	235.0	.00182	.00213
.85567	240.0	.00182	.00213
.85563	245.0	.00182	.00213
.85559	250.0	.00182	.00213
.85554	255.0	.00182	.00213
.85548	260.0	.00182	.00213
.85543	265.0	.00182	.00213
	.0	.00182	.00213
	0	.00182	.00213

NOZZLE HALF-ANGLE = 35.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.80886	25.0	.00172	.00213
.81557	30.0	.00173	.00213
.82073	35.0	.00174	.00213
.82485	40.0	.00175	.00213
.82823	45.0	.00176	.00213
.83105	50.0	.00177	.00213
.83346	55.0	.00177	.00213
.83553	60.0	.00178	.00213
.83734	65.0	.00178	.00213
.83894	70.0	.00178	.00213
.84035	75.0	.00179	.00213
.84161	80.0	.00179	.00213
.84275	85.0	.00179	.00213
.84377	90.0	.00179	.00213
.84470	95.0	.00180	.00213
.84555	100.0	.00180	.00213
.84632	105.0	.00180	.00213
.84703	110.0	.00180	.00213
.84768	115.0	.00180	.00213
.84828	120.0	.00180	.00213
.84884	125.0	.00180	.00213
.84935	130.0	.00181	.00213
.84983	135.0	.00181	.00213
.85027	140.0	.00181	.00213
.85068	145.0	.00181	.00213
.85106	150.0	.00181	.00213
.85142	155.0	.00181	.00213
.85175	160.0	.00181	.00213
.85206	165.0	.00181	.00213
.85235	170.0	.00181	.00213
.85263	175.0	.00181	.00213
.85288	180.0	.00181	.00213
.85312	185.0	.00181	.00213
.85334	190.0	.00181	.00213
.85355	195.0	.00181	.00213
.85374	200.0	.00181	.00213
.85415	205.0	.00182	.00213
.85432	210.0	.00182	.00213
.85448	215.0	.00182	.00213
.85463	220.0	.00182	.00213
.85477	225.0	.00182	.00213
.85490	230.0	.00182	.00213
.85503	235.0	.00182	.00213
.85515	240.0	.00182	.00213
.85526	245.0	.00182	.00213
.85536	250.0	.00182	.00213
.85546	255.0	.00182	.00213
.85555	260.0	.00182	.00213
.85563	265.0	.00182	.00213
.85571	270.0	.00182	.00213
.85579	275.0	.00182	.00213

NOZZLE HALF-ANGLE = 40.0 DEG
FPER = FNET/FMAX
(AE/AT)GEO = GEOMETRIC AREA RATIO
AO X CR = .0015 IN2
NOZZLE THROAT DIAMETER = .0100 IN
GAS INLET TEMPERATURE = 25.0 DEG C

FPER	ARTGEO	FNET (LB)	FMAX (LB)
.78922	25.0	.00168	.00213
.79683	30.0	.00169	.00213
.80277	35.0	.00171	.00213
.80757	40.0	.00172	.00213
.81156	45.0	.00172	.00213
.81494	50.0	.00173	.00213
.81786	55.0	.00174	.00213
.82040	60.0	.00174	.00213
.82265	65.0	.00175	.00213
.82465	70.0	.00175	.00213
.82645	75.0	.00176	.00213
.82808	80.0	.00176	.00213
.82956	85.0	.00176	.00213
.83091	90.0	.00177	.00213
.83215	95.0	.00177	.00213
.83329	100.0	.00177	.00213
.83435	105.0	.00177	.00213
.83533	110.0	.00178	.00213
.83625	115.0	.00178	.00213
.83710	120.0	.00178	.00213
.83790	125.0	.00178	.00213
.83865	130.0	.00178	.00213
.83935	135.0	.00178	.00213
.84002	140.0	.00179	.00213
.84064	145.0	.00179	.00213
.84123	150.0	.00179	.00213
.84179	155.0	.00179	.00213
.84232	160.0	.00179	.00213
.84282	165.0	.00179	.00213
.84330	170.0	.00179	.00213
.84375	175.0	.00179	.00213
.84418	180.0	.00179	.00213
.84460	185.0	.00180	.00213
.84504	190.0	.00180	.00213
.84542	195.0	.00180	.00213
.84578	200.0	.00180	.00213
.84613	205.0	.00180	.00213
.84645	210.0	.00180	.00213
.84677	215.0	.00180	.00213
.84707	220.0	.00180	.00213
.84736	225.0	.00180	.00213
.84764	230.0	.00180	.00213
.84791	235.0	.00180	.00213
.84817	240.0	.00180	.00213
.84842	245.0	.00180	.00213
.84865	250.0	.00180	.00213
.84888	255.0	.00180	.00213
.84910	260.0	.00180	.00213
.84932	265.0	.00181	.00213
.84952	270.0	.00181	.00213
.84972	275.0	.00181	.00213

Nomenclature

Symbol	Computer equivalent	Variable
A_1	A1	valve dimension, in. (see Fig. A-1)
A_2	A2	valve dimension, in. (see Fig. A-1)
A_e	AE	nozzle geometric exit area, in.^{2}
A_o	AO	effective valve orifice area, in.^{2}
$(A_o)(CDV)$	AOCR	product of A_o and valve orifice discharge coefficient, in.^{2}
A_{oz}	AOX	valve seat area, in.^{2}
	ARITER	iterated aerodynamic nozzle area ratio
$(A_e/A_t)_{aero}$	ARTERO	aerodynamic nozzle area ratio
$(A_e/A_t)_{geo}$	ARTGEO	geometric nozzle area ratio
A_t	AT	nozzle geometric throat area, in.^{2}
B	B	valve dimension, in. (see Fig. A-1)
C_{dv}	CDV, CR	valve orifice discharge coefficient
C_E	CE	nozzle exit speed of sound, in./s, $= (\gamma g_o R T_E)^{1/2}$
	CFP	partial flow expansion equation constant
C_F	CF	see Eq. (42)
	CPC	chamber pressure equation constant
C_V	CV	specific heat of constant volume, ft^2/s^2-°R
D_B	DB	valve orifice ball diameter, in.
D_E	DE	nozzle exit diameter, in.
$dF(M_E)$	DFCN	derivative of Mach # Eq. (23)
$dF(P_c)$	DFPC	derivative of chamber pressure Eq. (20)
	DLT	number of units in graph title
	DLX	number of units in X-axis title
	DLY	number of units in Y-axis title
D_s	DS	valve orifice seat diameter, in.
D_t	DT	nozzle throat diameter, in.
	DX	number of units in X-axis labels
	DY	number of units in Y-axis labels
E	E	valve dimension, in. (see Fig. A-1)
F		thrust Eq. (34)
$f(M_E)$	FCN	Mach number Eq. (21)
	FGAM	function of $\gamma - (\gamma + 1)/(\gamma - 1)$
	FLON2	floating point equivalent of N_2

Nomenclature (contd)

Symbol	Computer equivalent	Variable
$f(P_c)$	FPC	chamber pressure Eq. (17)
F_{max}	FMAX	see Eq. (43)
F_{net}	FNF	net thrust, lb [see Eq. (45)]
F_{per}	FPER	percent thrust of FMAX or FREF
F_{ref}	FREF	net thrust at reference conditions
F_{theor}	FTHEOR	see Eq. (41)
g_o	GO	acceleration of gravity, in./s^2
H	H	valve dimension, in. (see Fig. A-1)
	IC	plot grid format
	IL	plot label format
	IN1	chamber pressure iteration counter
	IN2	Mach number iteration counter
	IN3	boundary layer iteration counter
L, ℓ	SL	nozzle length, in.
L_ζ	FDEL	boundary layer thrust loss ratio
L_N	FN	non-parallel exit flow thrust loss ratio
L_P	FP	partial flow expansion thrust loss ratio
L_T	FLTOT	total thrust loss ratio (see Eq. 44)
	FLTOTP	total thrust loss ratio (percent)
	MAX1	chamber pressure iteration limit
	MAX2	Mach number iteration limit
	MAX3	boundary layer iteration limit
M_E	CN	nozzle exit plane Mach number
$(M_E)_{init}$	CNINIT	initial nozzle exit Mach number iteration value
$(M_E)_N$	CNN	nth iteration of exit Mach number
	N1	number of plot curves per graph
	N2	number of data points per curve
	N3	number of curve increments
P_A	PA	ambient pressure, lb/in.^{2}
P_c	PC	valve chamber pressure, lb/in.^{2}
$P_{c(init)}$	PCINIT	initial chamber pressure iteration valve, lb/in.^{2}
$P_{c(n)}$	PCN	nth iteration of chamber pressure
P_E	PE	nozzle exit pressure, lb/in.^{2}
P_o	PO	valve inlet pressure, lb/in.^{2}
Q	Q	valve dimension (see Fig. A-1)
R	R	nitrogen gas constant 55.16 ft-lb$_f$/lb$_m$-°R

Nomenclature (contd)

Symbol	Computer equivalent	Variable
R_b	RB	valve orifice ball radius, in.
R_E	RE	nozzle exit plane radius, in.
$(R_*)_{eff}$	REEFF	aerodnyamic nozzle exit radius, in.
$R\#$	RENO	Reynolds number
$R\#/L/P_c$	RENOU	Reynolds number/unit nozzle length/unit chamber pressure ft/lb
R_s	RS	valve orifice seat radius, in.
R_t	RT	nozzle throat radius, in.
T_o	TO	inlet stagnation gas temperature, °C
T_B	TB	valve ball travel, in.
T_E	TE	nozzle exit temperature, °R
T_R	TR	inlet stagnation gas temperature, °R
T_{rat}	TRAT	$T_R T_E$
V		velocity, in./s (see Eqs. 4 and 7)
V_E	VE	nozzle exit velocity, in./s
V_{EF}	VEF	nozzle exit velocity, ft/s
	WRAT	flow rate/flow rate at 25°C
	XINC	X-axis graph increment, in.
	XL	initial X-axis label value
	XLEN	X-axis physical length, in.
	XMIN	X-axis minimum value
	XMAX	X-axis maximum value
	XPOSX	X-axis coordinate of initial X-axis label
	XPOSY	X-axis coordinate of initial Y-axis label
	XSF	X-axis scale factor
	YINC	Y-axis graph increment, in.
	YL	initial Y-axis label value
	YLEN	Y-axis physical length, in.
	YMIN	Y-axis minimum value
	YMAX	Y-axis maximum value
	YPOSX	Y-axis coordinate of initial X-axis label
	YPOSY	Y-axis coordinate of initial Y-axis label
	YSF	Y-axis scale factor
γ	GAMMA	ratio of specific heats
ΔP	DELP	(inlet pressure-chamber pressure), psi
δ	DELTA	boundary layer momentum thickness, in.

Nomenclature (contd)

Symbol	Computer equivalent	Variable
δ^*	DELSTR [DELTASTAR]	boundary layer displacement thickness, in.
ϵ_1	EPS1	chamber pressure iteration accuracy value
ϵ_2	EPS2	Mach number iteration accuracy value
ϵ_3	EPS3	boundary layer iteration accuracy value
μ_o	UO	absolute viscosity, lb-s/ft^2
Π	PI	ratio of circumference to diameter of circle
σ	SIGDEG	nozzle half-angle, deg
σ_{eff}	SIGEFF	aerodynamic nozzle half-angle, radians
σ	SIGMA	geometric nozzle half-angle, radians
Φ_2	PHI2	valve dimensions (see Fig. A-1)
ω_t	WTDOT	nozzle weight flow rate, lb/s
ω_v	WODOT	valve orifice weight flow rate, lb/s

Subscripts

a	ambient
aero	aerodynamic
c	valve chamber
e	nozzle exit plane
geo	geometric
eff	effective
init	initial
iter	iteration
max	maximum
N	iteration number
o	inlet
per	percent
r	Rankine
rat	ratio
ref	reference
t	nozzle throat
theor	theoretical

References

1. Greer, H., and Griep, D. J., *Low Thrust Reaction Jet Performance,* Report No. TDR-469 (5230-33)-2, Aerospace Corporation, El Segundo, Calif., Aug. 1965.
2. McCormick, John M., and Salvadori, Mario G., *Numerical Methods in Fortran,* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1965.
3. Ames Research Staff, *Equations, Tables, and Charts for Compressible Flow,* Report 1135, National Advisory Committee for Aeronautics, Moffett Field, Calif., 1953.
4. Mack, Leslie M., *Calculation of the Laminar Boundary Layer on an Insulated Flat Plate by the Klunker-McLean Method,* Progress Report No. 20-352, Jet Propulsion Laboratory, Pasadena, Calif., July 7, 1958.
5. Sutton, George P., *Rocket Propulsion Elements,* John Wiley & Sons, Inc., New York, 1956.
6. Bromberg, M. L., Jeffries, N. P., and Cumbers, L. L., *Research on Electrothermal Thrusters for Attitude Control Systems,* Report No. R63FDP288, General Electric Company, Cincinnati, Ohio.